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AD-A141 402

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A RAIN SCAVENGING MODEL FOR PREDICTING LOW YIELD AIRBURST WEAPON FALLOUT FOR OPERATIONAL TYPE STUDIES

THESIS

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THESIS

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

in Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Nuclear Engineering

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Captain, USA

March 1984

Preface

The purpose of this study project was to develop a simple method of predicting fallout from a low yield, nuclear airburst that would be useful to a tactical ground commander. Simple calculation methods exist for tactical use; however, none are utilized for airbursts. A computer model was developed based on low yield test data. The method produces maximum dose rate and infinite dose curves enabling a commander to quickly identify radiation hazard areas.

I thank LCDR James H. Gogolin and Capt Arthur T. Hopkins for their contributions to the lively art of fallout conversation and providing constructive criticism during this study. I particularly want to express my appreciation and thanks to Dr. Charles J. Bridgman for his guidance and sage advice in insuring that the cart always stayed behind the horse. Lastly, I want to thank my wife, Elsa, who always made sure that there was a light still flickering at the end of the tunnel.

Curtis R. Krieser

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Abstract

A method was developed that enables a tactical ground commander to predict gamma radiation dose rates and infinite doses produced by the rain scavenging of low-yield nuclear airburst clouds. A ground activity distribution per unit area at time t, A(x,y,t), is computed using a distribution of activity in the cloud per meter of altitude, A(z,t). To find the maximum activity grounded, it is assumed 100 percent of the cloud activity is instantaneously deposited on the ground by the mechanism of rain scavenging. This maximum A(x,y,t) is then converted to a maximum dose rate, $\dot{D}(x,y,t)$, from which maximum infinite doses are computed. Maximum dose rate and infinite dose curves vs cloud washout time (after cloud stabilization) are presented for 10 weapon yields ranging from 1.0 kiloton to 0.1 kiloton. It is shown that the radiation hazard levels are insignificant tactical threats at times greater than 36 hours after cloud stabilization.

A RAIN SCAVENGING MODEL FOR PREDICTING LOW YIELD AIRBURST WEAPON FALLOUT FOR OPERATIONAL TYPE STUDIES

I. Introduction

The ability to predict fallout from the atmospheric detonation of low yield nuclear weapons plays an important role in tactical planning and operations. A tactical ground commander must have the capabilit o predict radiological contamination hazard areas resulting from the friendly or unfriendly employment of nuclear weapons. These hazard a s are capable of producing mass casualties. Since actions must be taken to minimize the casualty producing effects of these hazard areas to friendly forces, the tactical ground commander must be able to predict the location and intensity of the hazard.

Currently a method exists that allows ground commanders to predict fallout hazard areas for all types of nuclear weapon bursts except an airburst (Ref 5). When an airburst is employed no tactically significant fallout will occur because airburst fallout particles are too small to be deposited locally on the battlefield. However, if a rain (or snow) cloud interacts with the nuclear fallout cloud (scavenging the cloud), then tactically significant fallout could result. A simple method useful to a tactical ground commander for predicting low yield weapon fallout due to rain scavenging does not currently exist (Ref 6:B-12).

This thesis develops a simple rain scavenging fallout model for the tactical commander. For the purpose of this thesis, low yields will be defined as being less than or equal to 1 kiloton. Section II provides an introduction to the two principle types of fallout models currently in use. Section III explains the concept of the stabilized cloud and describes a low yield cloud model based on empirical weapons test data. Section IV describes the rain scavenging model for airbursts. Section V contains the results of this model and presents a method which a tactical ground commander can use in assessing the radiological hazard to his troops.

II. Types of Fallout Models

This section describes the two types of fallout models presently in use. The first type is the numerical model represented by the Department of Defense Land Fallout Interpretive Code (DELFIC) (Ref 12). The second type is the analytical model represented by both the Pentagon Weapon Systems Evaluation Group (WSEG) and Air Force Institute of Technology (AFIT) codes (Refs 14, 3).

Numerical Model (DELFIC)

DELFIC is a full physics computer code developed for use as a research tool (Ref 12:2). DELFIC models the fallout process by computing the space-time history of fallout particles as they are transported through the atmosphere and down toward the earth's surface. These fallout particles are represented by pancake shaped wafers containing distinct particle size groups. The fallout pattern on the ground at a given time is computed by superpositioning the ground positions of those wafers that have reached the ground in that given time. Because DELFIC must carry out a large number of calculations, it is a slow running code and very expensive to use. To alleviate this problem, faster running analytical codes have evolved.

Analytical models (WSEG and AFIT)

The WSEG and AFIT codes, unlike DELFIC, model the fallout particle deposition by smearing the stabilized radioactive cloud on the ground as it falls. The resulting fallout pattern on the ground is illustrated by the shaded area in Figure 1.

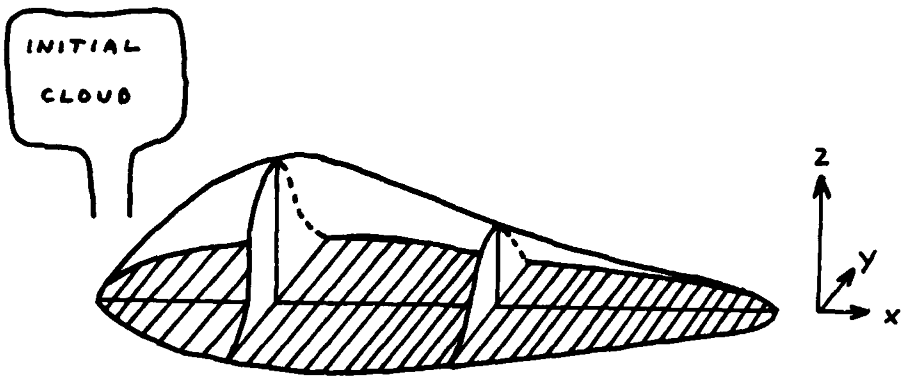

Figure 1. Fallout Contour From a Constant Wind (Ref 10:2)

This smearing of the fallout cloud on the ground surface produces an activity distribution per unit area, $A(x,y,t)$, that can be found from

$$A(x,y,t) = A_t(t) \int_0^t f(x,y,t)g(t)dt \qquad (1)$$

where $A_t(t)$ represents the total activity in the cloud at time t and g(t) is the fractional arrival rate of activity on the ground (Ref 3:207).

The function $f(x,y,t)$ represents the horizontal distribution of activity in the cloud. It is a dual normal function with a standard deviation in both the downwind or x direction and the crosswind or y direction (Ref 3:208). These standard deviations are functions of the fallout cloud arrival time on the ground, $t = x/v_x$. The normalized horizontal activity distribution is represented by

$$f(x,y,t) = \frac{1}{\sqrt{2\pi}\ \sigma_x(t)} \exp\left\{ -\frac{1}{2}\left[\frac{x-v_x t}{\sigma_x(t)}\right]^2 \right\}$$

$$\cdot \frac{1}{\sqrt{2\pi}\ \sigma_y(t)} \exp\left\{ -\frac{1}{2}\left[\frac{y}{\sigma_y(t)}\right]^2 \right\} \qquad (2)$$

where v_x is assumed to be a constant wind velocity in the x direction.

Equation (1) is the fundamental equation used to compute fallout footprints from smearing codes. The function g(t) is the key element of this equation. An example of a surface burst g(t) calculation is illustrated in Figure 2 (Ref 3,12). The activity on the ground per unit area can then be converted to a dose rate in rads per hour at a detector 3 feet off the ground

$$\dot{D}(x,y,t) = C\ A(x,y,t) \qquad (3)$$

where $\dot{D}(x,y,t)$ is the dose rate and C is a constant having units of rads per hour per unit activity per unit area (Ref 3:207). The derivation of the constant C can be found in Appendix A.

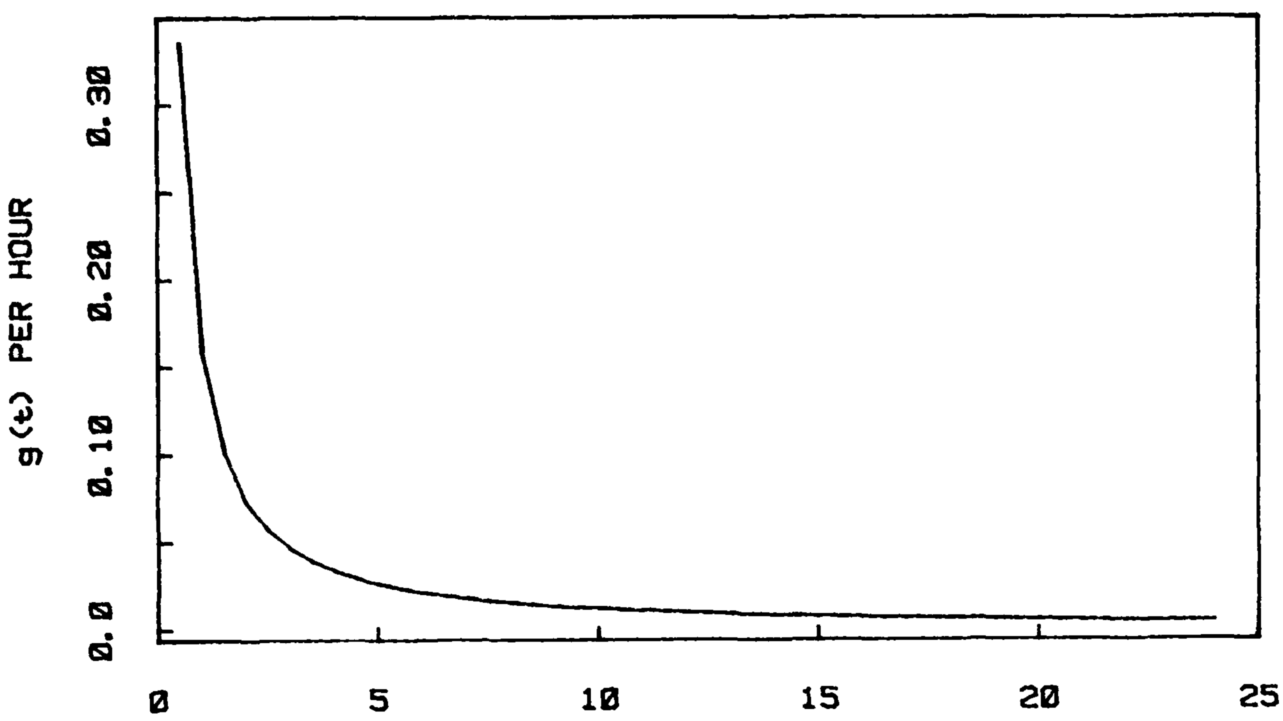

Figure 2. g(t) vs TIME for a 1.0 Kiloton Surface Burst

III. The Stabilized Nuclear Cloud

Background

The detonation of a nuclear weapon produces a very hot cloud of radioactive weapon debris and incandescent air called the fireball. This fireball rises, expands, and cools mainly by radiation convection mixing of hot and cool air. When thermodynamic equilibrium is reached with the ambient atmosphere, the cloud ceases to rise and becomes stabilized.

In a surface burst, large amounts of surface material are lofted into the cloud and vaporized. As the fireball cools, the radioactive constituents become mixed and incorporated into the surface debris by condensation. The resulting particles then fall to the earth. Figure 3 illustrates the DELFIC number-size distribution of particles resulting from a surface burst. In an airburst, where the fireball does not intersect the ground, there are no large amounts of surface debris lofted into the cloud. As a result, the particles are much smaller and less widely distributed in size as shown in Figure 4. These particles descend to the earth at a much slower rate than particles produced by a surface burst (Ref 8:36).

Cloud Center Height

The WSEG and AFIT smearing codes allow fallout particles to begin their descent from an altitude that corresponds to the initial stabilized cloud center height. This stabilized cloud center height is modeled using an empirical function of the form

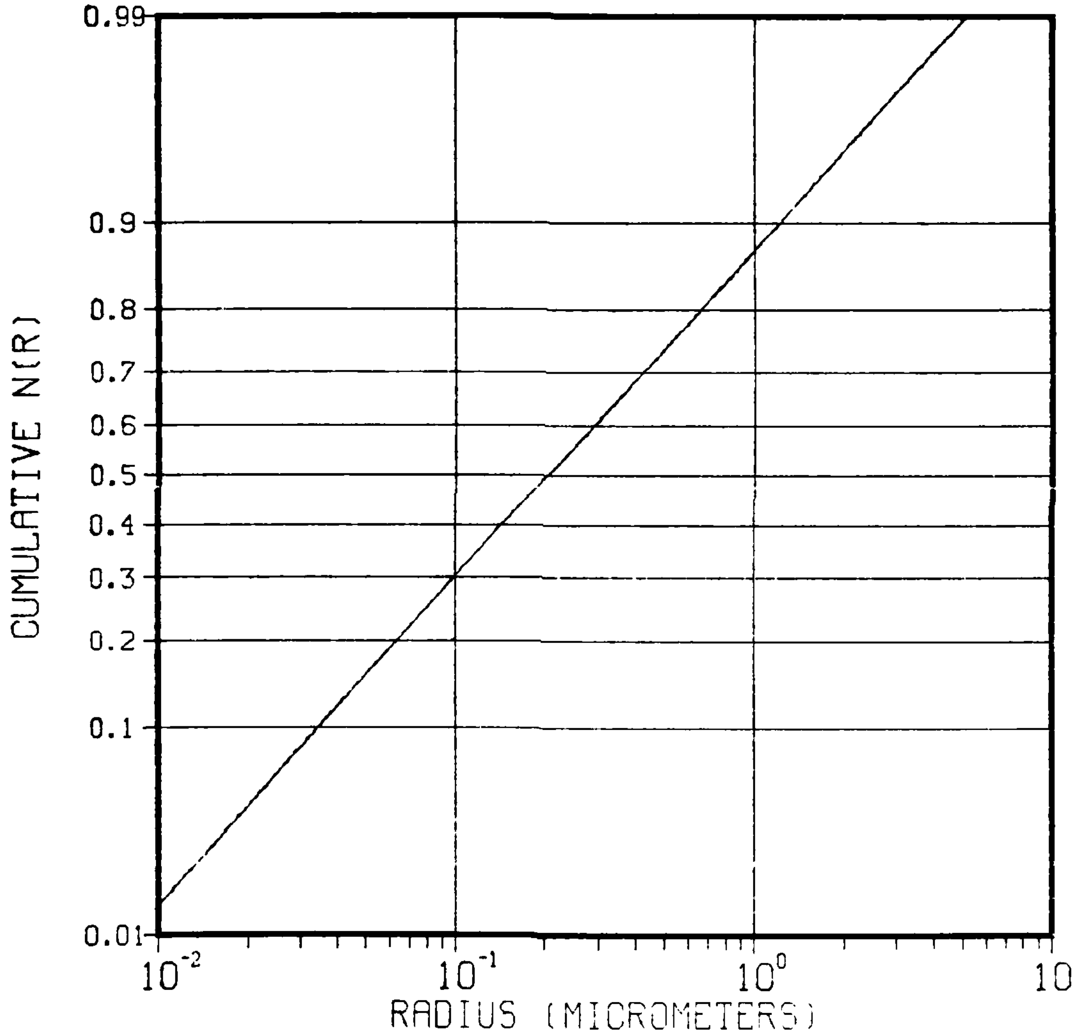

Figure 3. Cumulative Number-Size Distribution for a Surface Burst

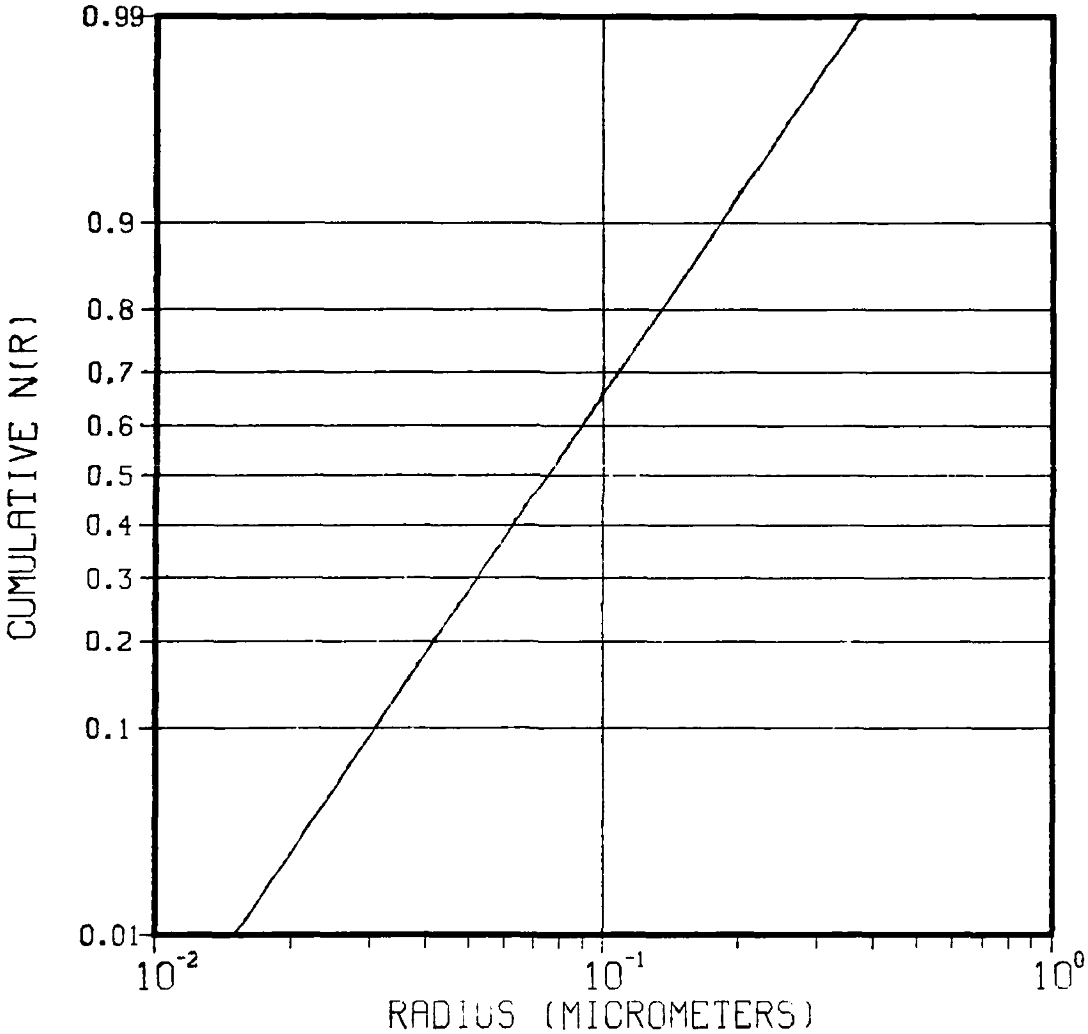

Figure 4. Cumulative Number-Size Distribution for an Airburst

$$HC = 44.0 + 6.1 \ln Y - .205(\ln Y + 2.42) \left| \ln Y + 2.42 \right| \qquad (4)$$

where Y is the weapon yield in megatons and HC is the cloud center height in kilofeet (Ref 3:213). This relation, when applied to yields of 1 kiloton or less, produces questionable results as is pointed out in the WSEG documentation (Ref 14:31). For example, a weapon having a 0.2 kiloton yield is predicted to have a stabilized cloud center height of -0.33 kilofeet.

A remedy to this dilemma was to compile visible cloud data from 22 low yield airburst tests conducted between 1945 and 1962. This data was originally compiled by the old Defense Atomic Support Agency (DASA) and contained in its 1251 series of reports (Ref 9). The data is summarized in Table I. A polynomial least squares fit of the data was performed to obtain a cloud center height relation as a function of yield. It was assumed, as in the WSEG model, that the center of the radioactive cloud is located at the same altitude as the bottom of the visible cloud (Ref 14:24). The resulting fit is a polynomial of fourth degree having the form

$$HC = 8.30476298 + .63632921 \ln Y - .39763749 (\ln Y)^2$$
$$- .01364081 (\ln Y)^3 + .00560846 (\ln Y)^4 \qquad (5)$$

where Y is the weapon yield in kilotons and HC is the stabilized cloud center height in kilofeet. Unless otherwise stated, Y will have the dimensions of kilotons. Figure 5 illustrates this functional fit along with the data extracted from DASA 1251. It should be noted that equation (5) provides best results for yields ranging between 0.01 kilotons

Table I

Visible Cloud Data Extracted From DASA 1251

TEST NAME	YIELD (Kt)	SITE ELEVATION (ft)	HEIGHT OF BURST (ft)	CLOUD BOTTOM HEIGHT (ft MSL)
Buster Jangle-Able	.1	4169.17	100.0	6700.0
Tumbler Snapper-Baker	1.0	4193.0	1109.0	10000.0
Upshot Knothole-Ruth	.2	4000.0	304.69	10700.0
Upshot Knothole-Ray	.2	4026.0	100.0	7700.0
Teapot-Wasp	1.0	4195.0	762.0	14500.0
Teapot-Moth	2.0	4026.0	300.0	15900.0
Teapot-Post	2.0	4236.0	300.0	12000.0
Plumbbob-Franklin	.14	4026.0	300.0	14000.0
Plumbbob-Wheeler	.197	4230.0	500.0	14000.0
Plumbob-LaPlace	1.0	4186.0	750.0	14000.0
Hardtack II-Eddy	.083	4186.0	500.0	7500.0
Hardtack II-Mora	2.0	4186.0	1500.0	10000.0
Hardtack II-Hidalgo	.077	4186.0	377.0	8000.0
Hardtack II-Quay	.079	4249.0	100.0	7500.0
Hardtack II-Hamilton	.0012	3080.0	50.0	4500.0
Hardtack II-Rio Arribo	.09	4010.0	72.5	11000.0
Hardtack II-Wrangell	.115	3077.0	1500.0	7000.0
Hardtack II-Catron	.021	4026.0	72.5	5000.0
Hardtack II-Sanford	4.9	3077.0	1500.0	12500.0
Hardtack II-Debaca	2.2	4186.0	1500.0	10000.0
Hardtack II-Humboldt	.0078	4029.0	25.0	6000.0
Hardtack II-Santa Fe	1.3	4186.0	1500.0	13000.0

and 1.0 kiloton. Improvements to the fit can be achieved by utilizing more test data. However, the availability of test data is limited as recorded visible cloud data was found to be incomplete.

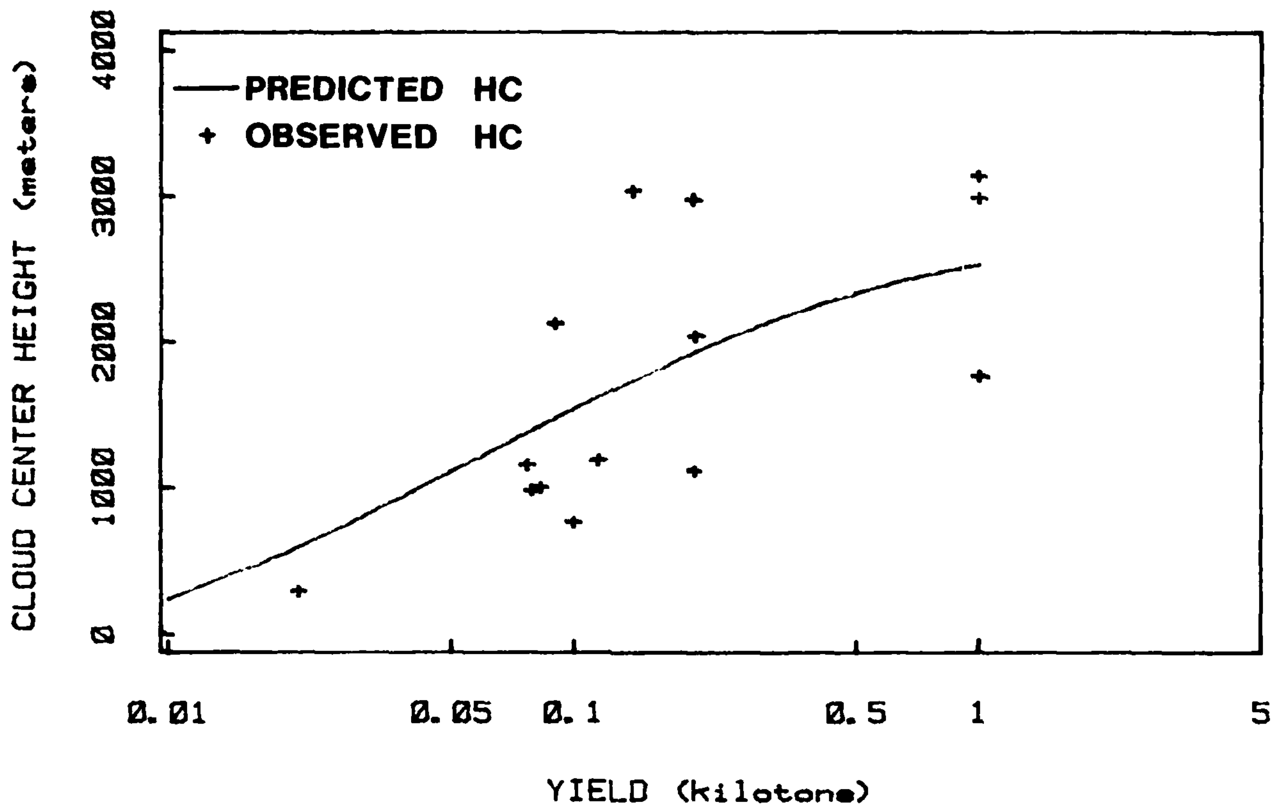

Figure 5. Empirical Fit to DASA 1251 Cloud Data

IV. The Airburst Scavenging Model

As mentioned earlier, the key element in computing grounded fallout activity in smearing codes is the function g(t). An illustration of g(t) for an airburst is shown in Figure 6. This g(t) might be compared to Figure 2 for a surface burst in Section II. It can be seen that the airburst, with its smaller particles, leads to a steady fall over months instead of hours. This would occur in a quiescent atmosphere. In actuality, the atmosphere is very turbulent. Airburst particles may experience downdrafts, updrafts, etc. that may preclude their being grounded. The only mechanism left for grounding of the activity is scavenging of the radioactive cloud by rain (or snow). The conclusion to be drawn here is that viscous fall of very small particles is a poor model for predicting airburst fallout. Instead, rain scavenging might be a more appropriate model. This section describes the computer model that predicts the maximum dose rate due to rain scavenging that can be encountered for an airburst.

Description

The rain scavenging model computes the initial stabilized cloud as described in Section III. The spatial distribution of activity in the cloud in curies/m^3 is described by

$$A(x,y,z,t_s) = A(z,t_s)\ f(x)\ f(y) \qquad (6)$$

where f(x) and f(y) are normalized Gaussian distributions in the x and y directions and $A(z,t_s)$ is the vertical distribution of cloud

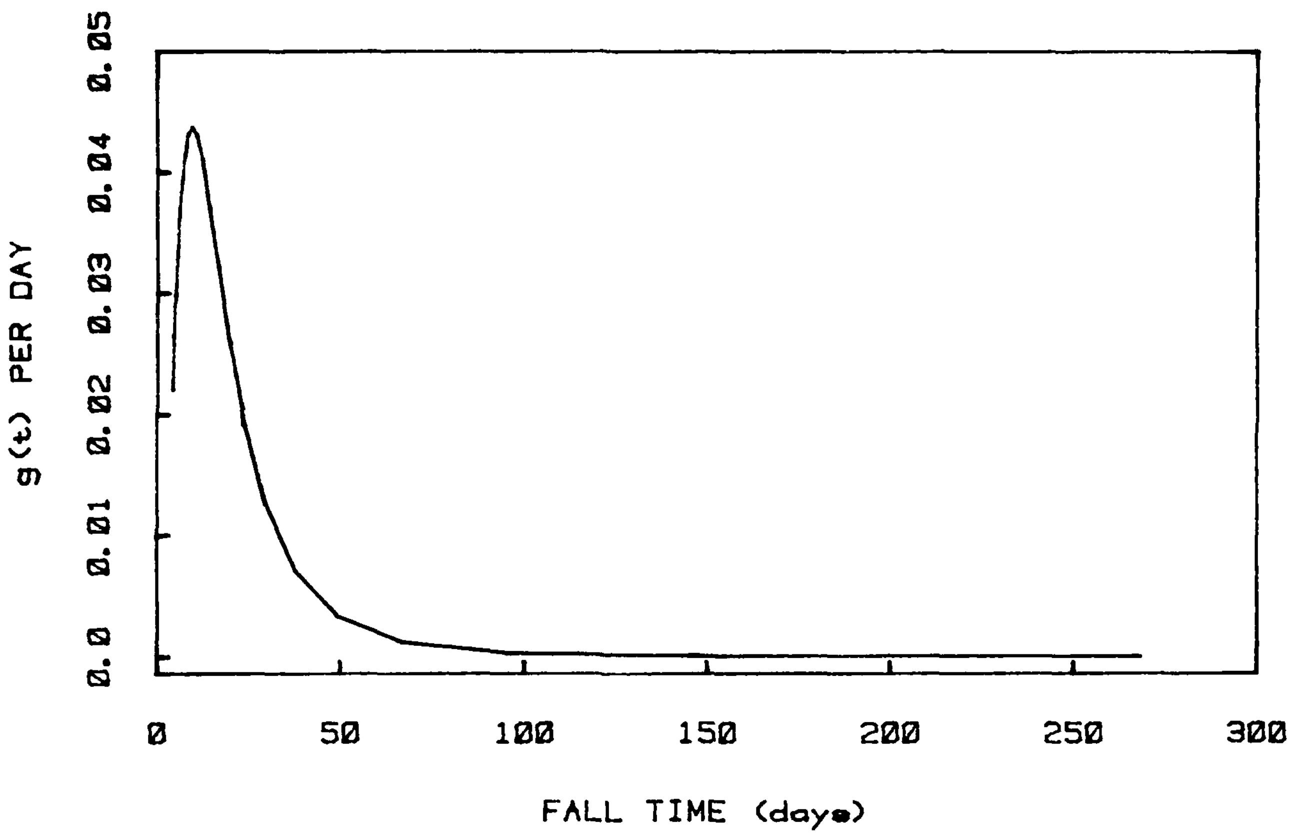

Figure 6. g(t) vs Fall Time for a 1.0 Kiloton Airburst

in curies/m at stabilization time t_s. At later times, the cloud is displaced in the x direction by a constant wind of velocity v_x. It is assumed that there is no y component of wind velocity. The spatial distribution of activity is then given by

$$A(x,y,z,t) = A(z,t)\ f(x)\ f(y) \tag{7}$$

If it is assumed a rain cloud washes out the radioactive cloud at time t by instantaneously depositing 100 percent of the activity onto the ground, then the horizontal distribution of activity on the ground per unit area is described by

$$A(x,y,t) = \left[\int_z^o A(z,t)dz\right]\ f(x)\ f(y) \tag{8}$$

The upper limit on the integral is taken to be zero since the integration is carried out from the top of the cloud z (at time t) to the ground.

Particle Number-Size and Activity-Size Distributions

Section III stated that airburst particles are much smaller than surface burst particles. Airburst particles are assumed to be spherical in shape and obey a lognormal distribution. The number-size distribution as a function of particle radius is expressed as

$$N(r) = \frac{1}{\sqrt{2\pi}\ \beta_o r} \exp\left[-\frac{1}{2}\left(\frac{\ln r - \alpha_o}{\beta_o}\right)^2\right] \tag{9}$$

where r is the particle radius in microns. The shaping parameters, α_o and β_o, are given by

Table II

Air Burst Number-Size Distributions

DISTRIBUTION NAME	GEOMETRIC STANDARD DEVIATION	GEOMETRIC MEAN PARTICLE RADIUS (microns)
Norment	2.0	.075
B	1.63	.105
C	1.77	.06
D-Sample 1	1.66	.10
D-Sample 2	1.67	.09
E	2.25	.055
F	1.85	.043
G	2.16	.0325
H	1.92	.0385

$$\alpha_\circ = \ln(r_{.5}) \tag{10}$$

$$\beta_\circ = \ln(\sigma) \tag{11}$$

where $r_{.5}$ is the geometric mean particle radius in microns and σ is the geometric standard deviation of the distribution (Ref 2). Airburst number-size distributions have been found by Norment (Ref 13:46) and Nathans (Ref 11:7567). The parameters for these distributions are shown in Table II. The distribution proposed by Norment with $\alpha_\circ = \ln(.075)$ and $\beta_\circ = \ln(2.0)$ will be used for all calculations made in this thesis.

The activity-size distribution is expressed as a weighted sum of two lognormal distributions

$$A(r) = f_v A_v + (1 - f_v)A_s \tag{12}$$

where A_v is the volumetric activity-size distribution, A_s is the surface activity-size distribution, and f_v is the volumetric fractionation ratio of total activity (Ref 3:210). The distributions A_v and A_s are proportional to the third and second moments of the particle size distribution respectively. Since the nth moment of a lognormal is also a lognormal distribution with the same value for $\beta_\circ$, the values of α_n can be computed from the relationship given by Aitcheson and Brown (Ref 2:12).

$$\alpha \;\; = \alpha_o + n\beta_o^2 \tag{13}$$

Russell (Ref 16:18) has suggested that smaller particles, typical of those found in airbursts, are often volumetrically distributed in activity. Taking this suggestion and assuming that activity in airburst particles is totally distributed volumetrically, $f_v = 1.0$, equation (12) simplifies to

$$A(r) = \frac{1}{\sqrt{2\pi}\,\beta_\circ r} \exp\left[-\frac{1}{2}\left(\frac{\ln r - \alpha_3}{\beta_\circ}\right)^2 \right] \tag{14}$$

where $\alpha_3 = \ln(.317)$ and $\beta_\circ = \ln(2.0)$. This is the activity-size distribution that will be used in this thesis. The cumulative activity-size distribution is shown in Figure 7.

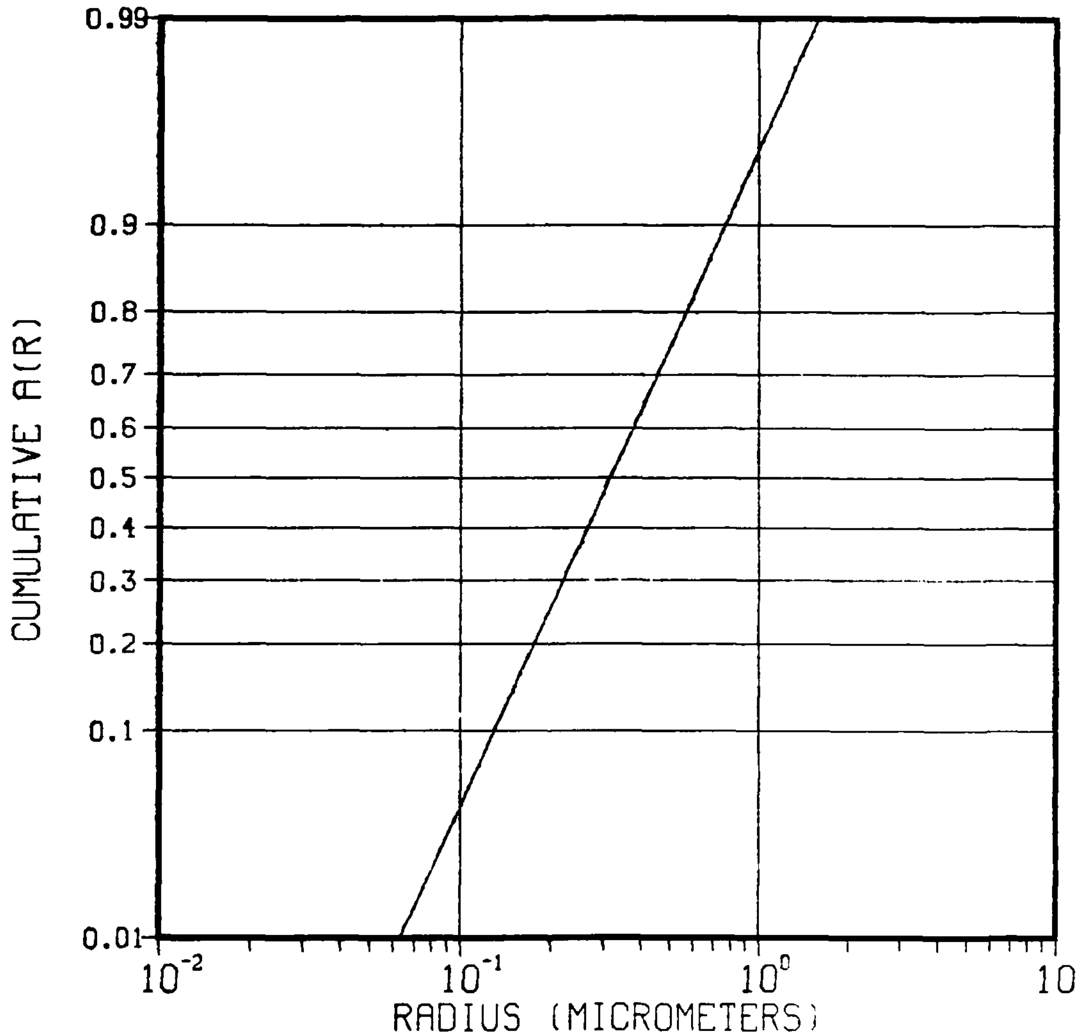

Figure 7. Cumulative Activity-Size Distribution

Calculation of A(z,t)

The vertical distribution of cloud activity per meter of altitude is computed using a method developed by Bridgman and Hickman (Ref 4:2) and is expressed as

$$A(z,t) = \int_0^\infty A(z,r,t)dr \tag{15}$$

where A(z,r,t) is the specific activity in curies per vertical meter of altitude per micron of radial size at time t. The integral in equation (15) can be replaced by a summation over a set number of discrete activity-size groups, each group containing an equal percentage of the total cloud activity at time t, where it is assumed each group contains monosized particles of mean radius r_i.

Since the activity-size distribution shown in Figure 7 has a small range of particle sizes, it can be divided into 10 discrete size groups, $A_i(t)$, each having 1/10 of the total cloud activity. Table III shows the values of the mean particle radii for each of these activity-size groups. Equation (15) can now be expressed as

$$A(z,t) = .10A_t \sum_{i=1}^{10} f_i(z,t) \tag{16}$$

where A_t is the total cloud activity and $f_i(z,t)$ is the normalized vertical activity distribution of each size group per meter of altitude at any given time t. The total cloud activity can be expressed using the

Table III

Activity-Size Groups

GROUP	MEAN PARTICLE RADIUS (microns)
1	.10
2	.16
3	.20
4	.24
5	.29
6	.35
7	.41
8	.51
9	.65
10	.99

Way-Wigner decay formula

$$A_t = A_1 \; Y \; t^{-1.2} \; (FF) \tag{17}$$

where A_1 is the gamma activity remaining per kiloton of fission yield one hour after weapon detonation, Y is the weapon yield in kilotons, and FF is the weapon fission fraction. Unless otherwise stated, FF will be assumed to be 1.0. The value for A_1 is taken to be 530 gamma megacuries per kiloton of fission (Ref 8:453). Since tissue dose rate is of interest, only the gamma activity is included in the calculation. The vertical

distribution of cloud activity in curies/m is now expressed as

$$A(z,t) = 530 \times 10^5 \, Y \, t^{-1.2} \sum_{i=1}^{10} f_i(z,t) \qquad (18)$$

The values of $f_i(z,t)$ are computed by assuming each size group to be initially situated at the stabilized cloud center height, HC. Each size group distribution is then allowed to fall through the atmosphere as a fixed body until it impacts on the ground, compressing much like an accordian.

<u>Fall Mechanics</u>

The fall velocity of each activity-size group can be computed directly using Stoke's Law fall mechanics. Stoke's Law can be used since the mean particle radius of each group is considerably less than 10 microns. Stoke's Law for free falling spheres in a viscous medium, namely the atmosphere, is

$$6 \pi \mu v r = \frac{4}{3} \pi \, r^3 \rho g \qquad (19)$$

where μ is the dynamic viscosity of the atmosphere in kg/m-sec, v is the particle fall velocity in m/sec, r is the particle radius in m, ρ is the particle density in kg/m^3, and g is the gravitational acceleration constant which has been set to 9.8 m/sec^2. The value for μ is altitude dependent. A method for calculating the dynamic viscosity utilizes the US Standard Atmosphere (Ref 17) and is shown in Appendix B. Solving for velocity gives

$$v = \frac{2r^2 \rho g}{9 \mu} \tag{20}$$

By replacing v in equation (20) with $\Delta z/\Delta t$, the altitude of each size group can be computed at different times t from

$$z_i(t) = HC - \sum_{j=1}^{n} v_i^j \, \Delta t^j \tag{21}$$

where

$$t = \sum_{j=1}^{n} \Delta t^j \tag{22}$$

The vertical distribution of cloud activity in curies/m can now be calculated from

$$A(z,t) = 530 \times 10^5 \; Yt^{-1.2} \sum_{i=1}^{10} \frac{1}{\sqrt{2\pi}\,\sigma_z} \exp\left[-\frac{1}{2}\left(\frac{z - z_i(t)}{\sigma_z}\right)^2\right] \tag{23}$$

where $\sigma_z = 0.18HC$, the standard deviation about the size group center height altitude as specified in WSEG (Ref 14:51).

Dose Rate Calculation

Equation (23) was evaluated at several different times. The profiles are shown in Figures 8 and 9. It can be seen that for times up to 5 days after cloud stabilization, the total cloud activity three standard deviations, σ_z, below the distribution center height still has not

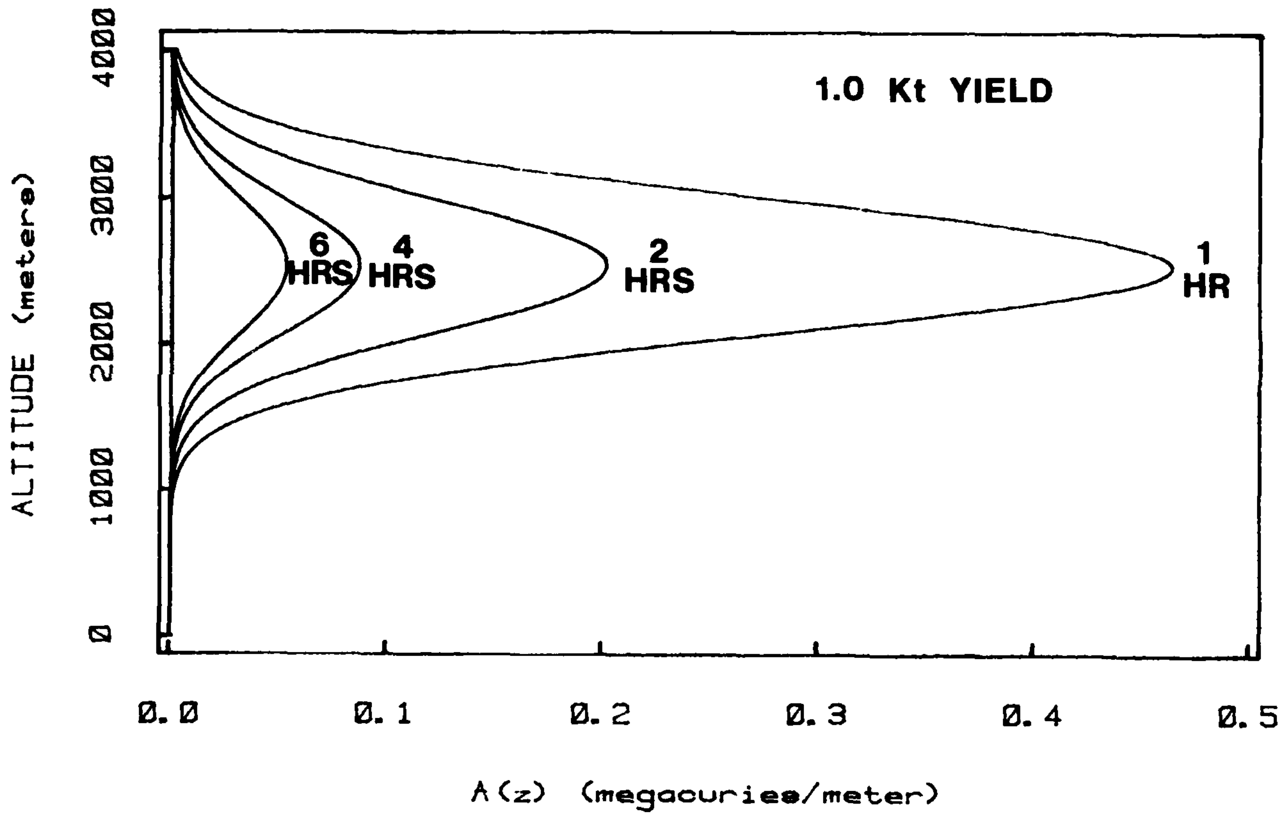

Figure 8. Distribution of Activity with Altitude

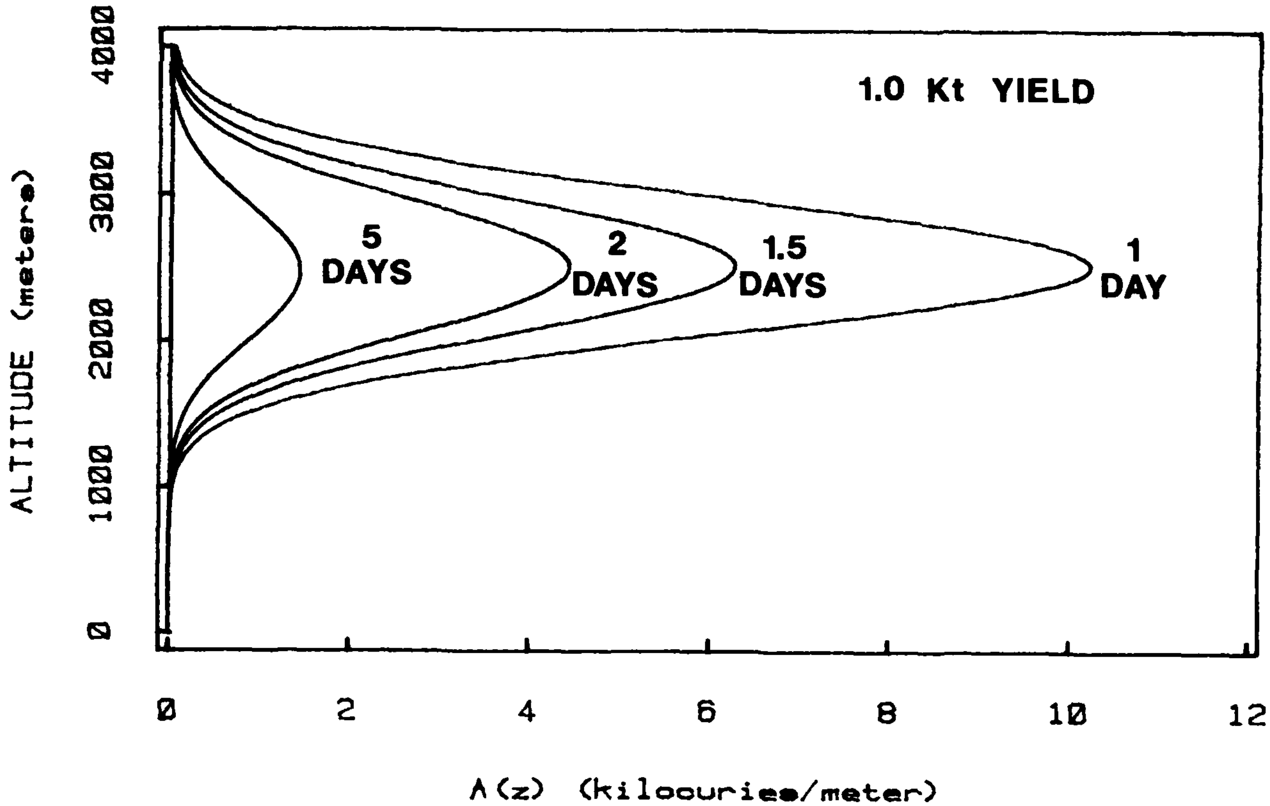

Figure 9. Distribution of Activity with Altitude

fallen below 500 m altitude. This indicates that an immersion dose due to an airburst is not a significant threat on the ground. Since all the cloud activity still resides in the air, equation (8) can be reduced to

$$A(x,y,t) = 530 \times 10^5 \; Yt^{-1.2} \; f(x) \; f(y) \tag{24}$$

Thus, equation (24) gives the ground distribution of activity per unit area due to total cloud washout. A worst-case scenerio will allow calculation of the maximum ground distribution of activity. By letting $x = v_x t$ and choosing $y = 0$, y lying on the fallout footprint hotline, the maximum activity grounded can be computed. The distributions in the x direction and y direction are now simplified to

$$f(x,t) = \frac{1}{\sqrt{2\pi}\,\sigma_x} \tag{25}$$

$$f(0,t) = \frac{1}{\sqrt{2\pi}\,\sigma_y} \tag{26}$$

These distributions are functions of time because the standard deviations σ_x and σ_y are functions of time. Values for σ_x and σ_y are computed in meters using the WSEG formulae (Ref 14:50).

$$\sigma_x(t) = \sqrt{\sigma_o^2 \left(1 + \frac{8t^*}{T_c}\right) + \left(\sigma_z \; S_x \; t\right)} \tag{27}$$

$$\sigma_y(t) = \sqrt{\sigma_o^2 \left(1 + \frac{8t^*}{T_c}\right) + \left(\sigma_z \; S_y \; t\right)} \tag{28}$$

where S_x and S_y represent wind shear in the x and y directions respectively. Wind shear is expressed in units of km/hr-km. By using the assumption of a constant wind in only the x direction and a wind shear only in the y direction, equation (27) simplifies to

$$\sigma_x(t) = \sqrt{\sigma_o^2 \left(1 + \frac{8t^*}{T_c}\right)} \tag{29}$$

The value for t* is limited to a maximum value of three hours. This limitation is made because the second term in equations (27) and (28) represents the toroidal growth of the cloud. This toroidal growth is assumed to cease after three hours (Ref 4:7). Values for σ_o are computed in meters using the yield dependent relationship expressed in WSEG (Ref 14:51)

$$\sigma_o = 1609 \exp\left[0.70 + \frac{1}{3}(\ln Y) - \frac{3.25}{4.0 + (\ln Y + 5.4)^2}\right] \tag{30}$$

where Y is the weapon yield in megatons. The WSEG time constant, T_c, is computed in hours using WSEG's own low yield correction (Ref 15:1)

$$T_c = \left[12\left(\frac{HC}{60}\right) - 2.5\left(\frac{HC}{60}\right)^2\right] \cdot \left\{1 - .5 \exp\left[-\left(\frac{HC}{25}\right)^2\right]\right\} \tag{31}$$

where HC is the stabilized cloud center height in kilofeet.

The maximum dose rate can now be computed using the peak grounded activity. This peak is illustrated in Figure 10. The dose rate is computed by multiplying this peak grounded activity by a constant as

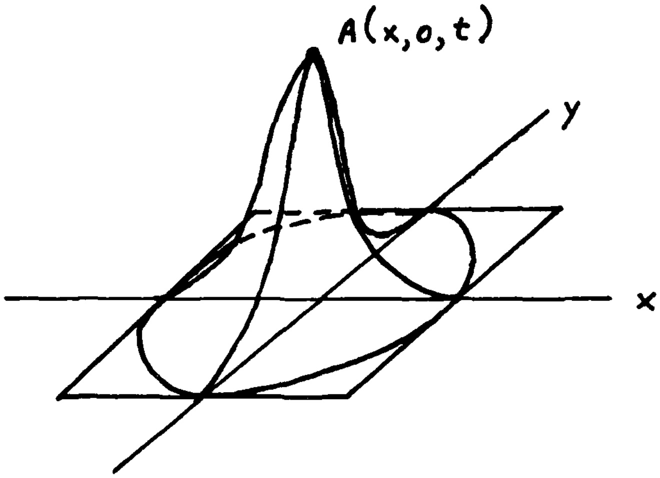

Figure 10. Peak Grounded Activity

shown in Appendix A. The dose rate is then given by

$$\dot{D}(x,o,t) = 14.4A(x,0,t) \tag{32}$$

The dose rate can also be expressed in terms of a unit time reference dose, UTRD, rate. This is the dose rate one hour after weapon detonation. The UTRD rate is expressed as

$$UTRD = \dot{D}(x,0,t)t^{1.2} \tag{33}$$

The UTRD can now be used to compute the accumulated dose to infinity. The dose to infinity is given by

$$DOSE = UTRD \int_{t}^{\infty} t^{-1.2} dt \tag{34}$$

where t represents the arrival time of the grounded activity.

V. Results

Base Case

A base case was established as a comparison standard. Yield was set at 1.0 kiloton using the Norment particle number-size distribution, α_o = ln (.075) and β_o = ln (2.0) . Fallout particle density was chosen to be 5500 kg/m³ (Ref 11:7565). All base case parameters are summarized in Table IV. The cloud washout time after stabilization was allowed to vary from 1 to 36 hours. The x coordinate of the cloud center point was set to a value $v_x t$ and then varied by factors of σ_x, $2\sigma_x$, and $3\sigma_x$. Since the f(x) distribution is a normal Gaussian, the dose rate and dose to infinity values are symmetric about the cloud center point in the x direction. The results of dose rate calculations for ten different yields are summarized and graphically displayed in Figures 11 through 20. Infinite dose calculations for these same yields are shown Figures 22 through 31 and can be found in Appendix D.

Table IV

Base Case Parameters

YIELD = 1.0 KILOTON	
WIND SHEAR IN THE Y DIRECTION = 1.0 KM PER KM PER HOUR	
DOWNWIND VELOCITY = 4.0 METERS PER SECOND	
VOLUMETRIC FRACTIONATION RATIO = 1.00	
PARTICLE MASS DENSITY = 5500. KILOGRAMS PER CUBIC METER	
ALPHA0 = LN(.075) = -2.590	BETA0 = LN(2.0) = .693
ALPHA2 = LN(.196) = -1.629	ALPHA3 = LN(.317) = -1.149

Parameter Variations

Several airburst particle number-size distributions shown in Table II were input into the rain scavenging model. The resulting dose rates and infinite doses reflect no change from the base case. This result is not surprising because of the very small radii of the particles. The particles will remain aloft for many days until scavenged from the cloud, regardless of the number-size distribution.

A change in particle mass density did not affect the dose rates or infinite doses. Again, this result is not surprising for the same reason stated above.

Downwind velocity was changed over a wind range of values. As expected, dose rates and infinite doses did not change. Changes in downwind velocity only displace the cloud center point to different locations.

Different values for wind shear in the y direction were inserted into the model. The dose rates and infinite doses calculated did change. As expected, a decrease in the wind shear results in an increase in the dose rate. As wind shear decreases, less cloud activity is displaced in the crosswind direction from the cloud center point on the ground allowing more activity to be deposited during scavenging.

Summary

The rain scavenging model provides a simple tool useful in predicting low yield, airburst fallout. A tactical ground commander need only know local wind data, weapon yield, ground zero, and time of actual or anticipated rain. With this information, maximum dose rates and doses at locations upwind and downwind from the center of grounded activity can be determined.

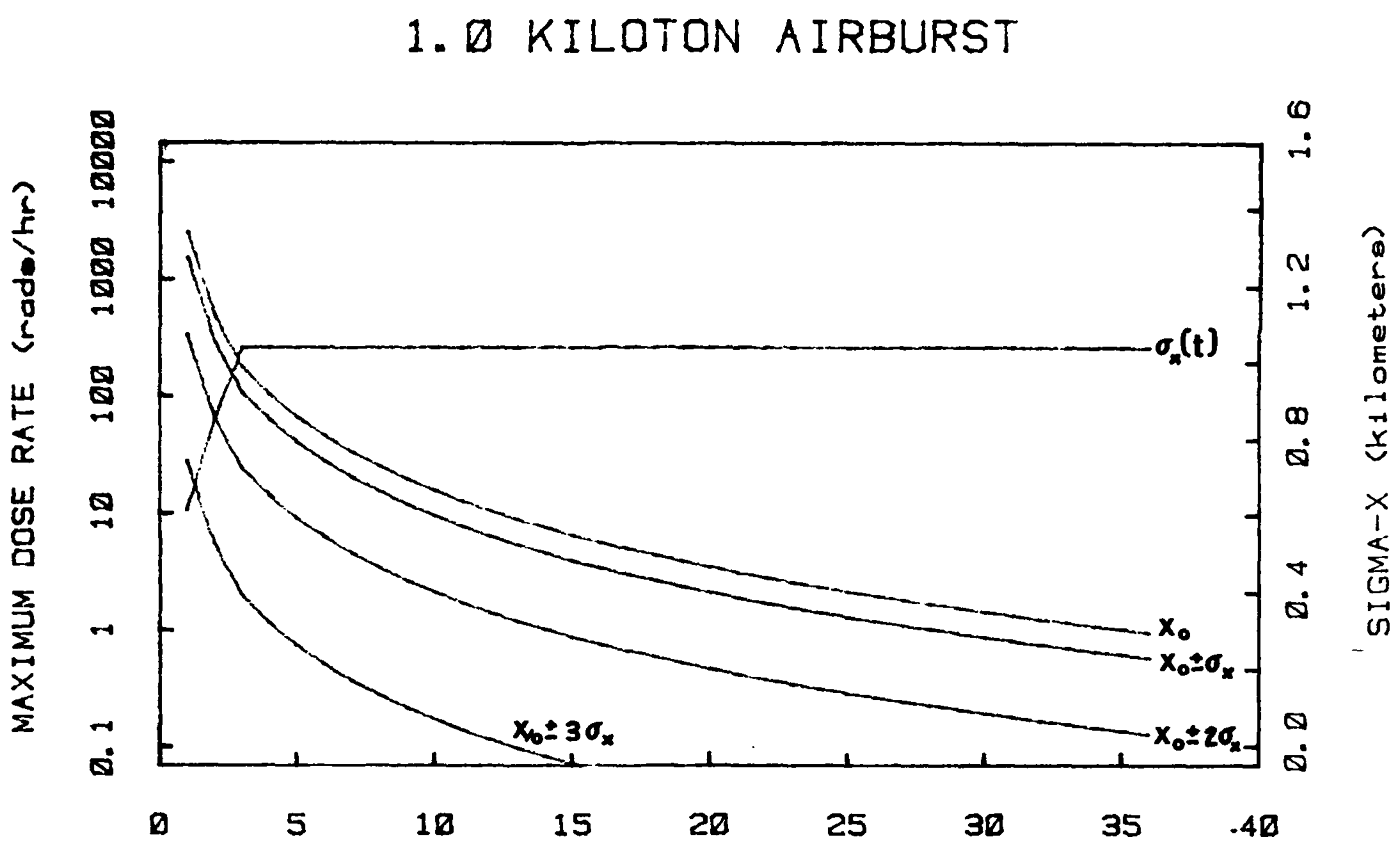

Figure 11. Maximum Dose Rate and Sigma-x Distance

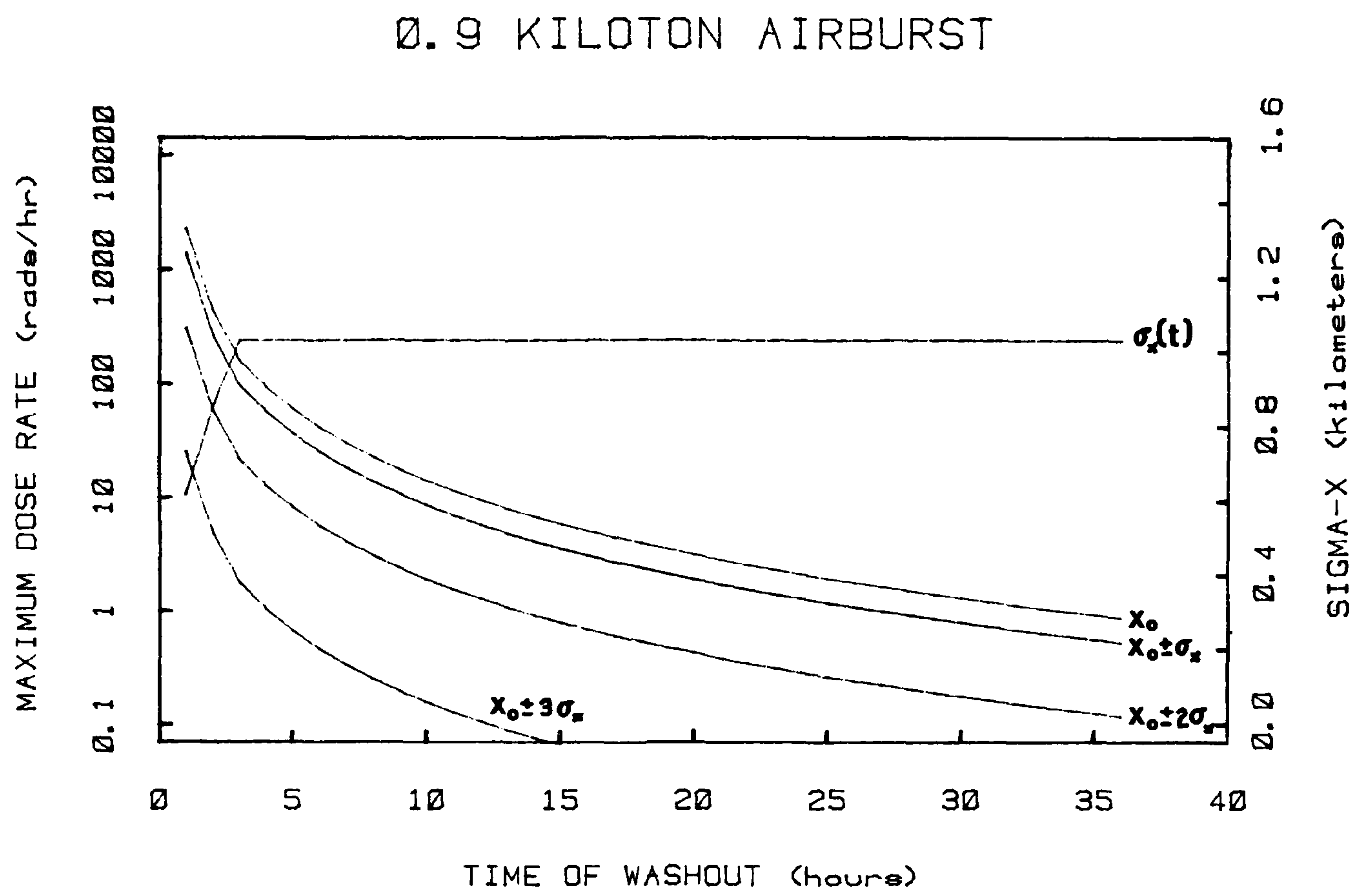

Figure 12. Maximum Dose Rate and Sigma-x Distance

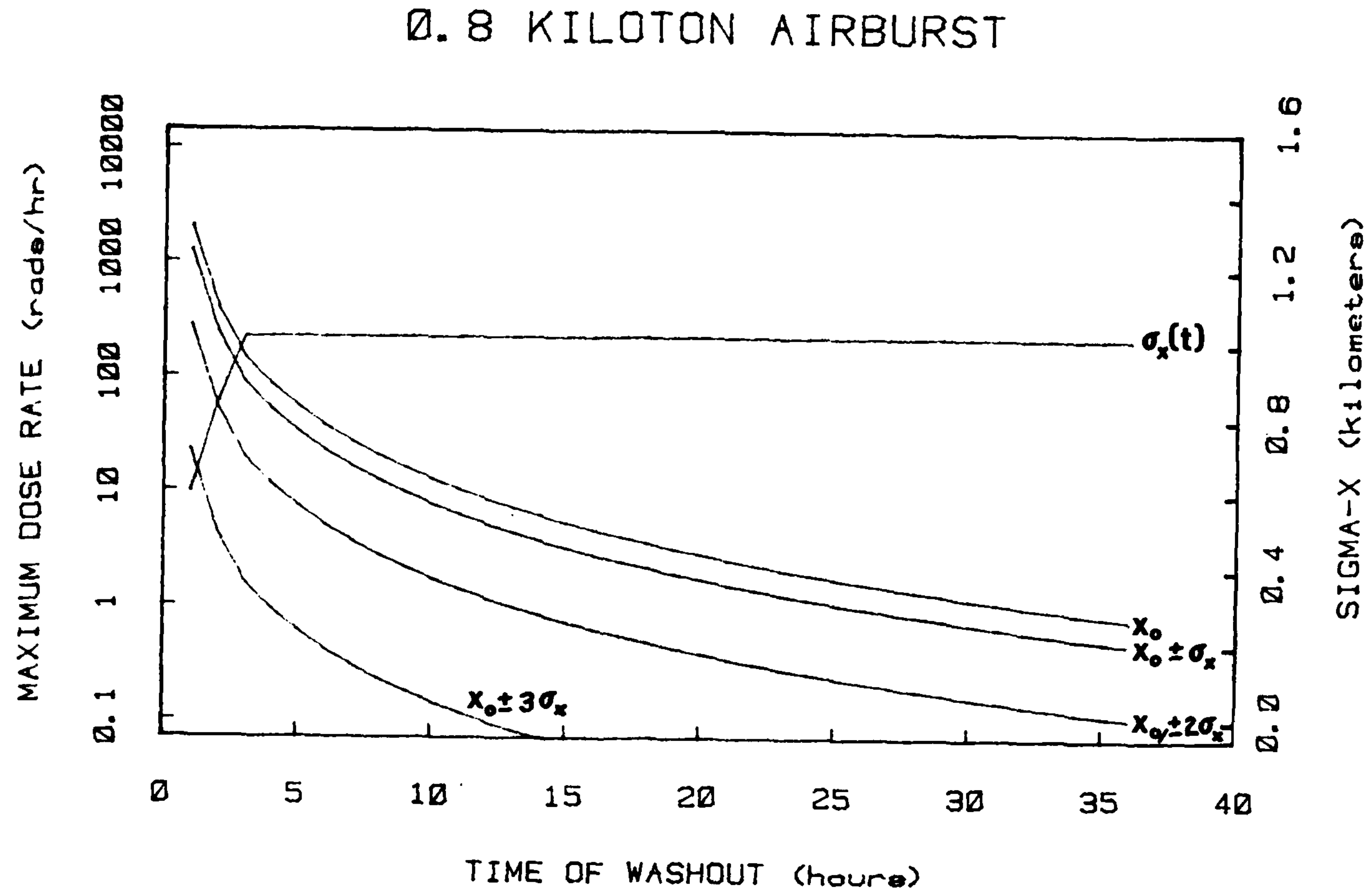

Figure 13. Maximum Dose Rate and Sigma-x Distance

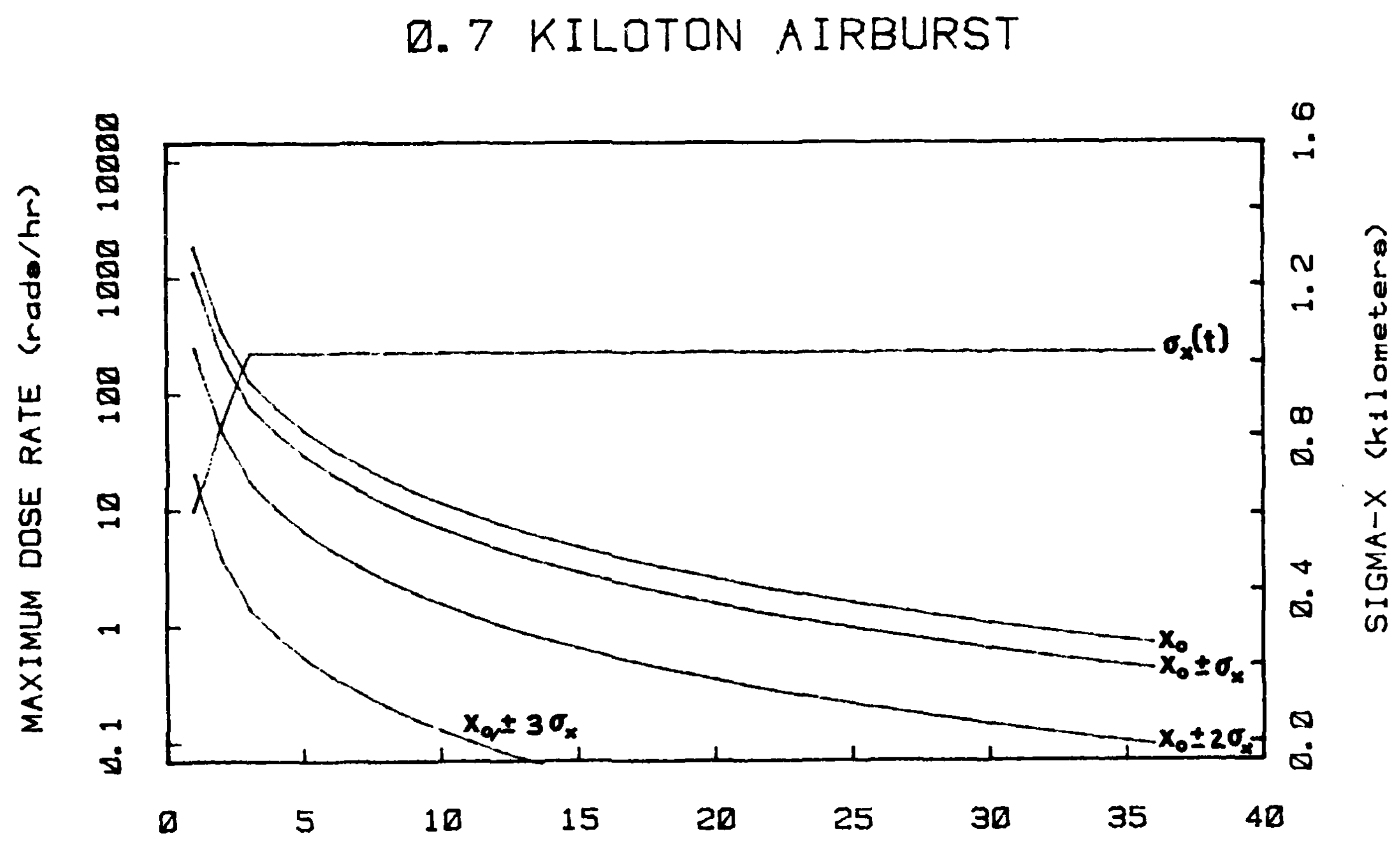

Figure 14. Maximum Dose Rate and Sigma-x Distance

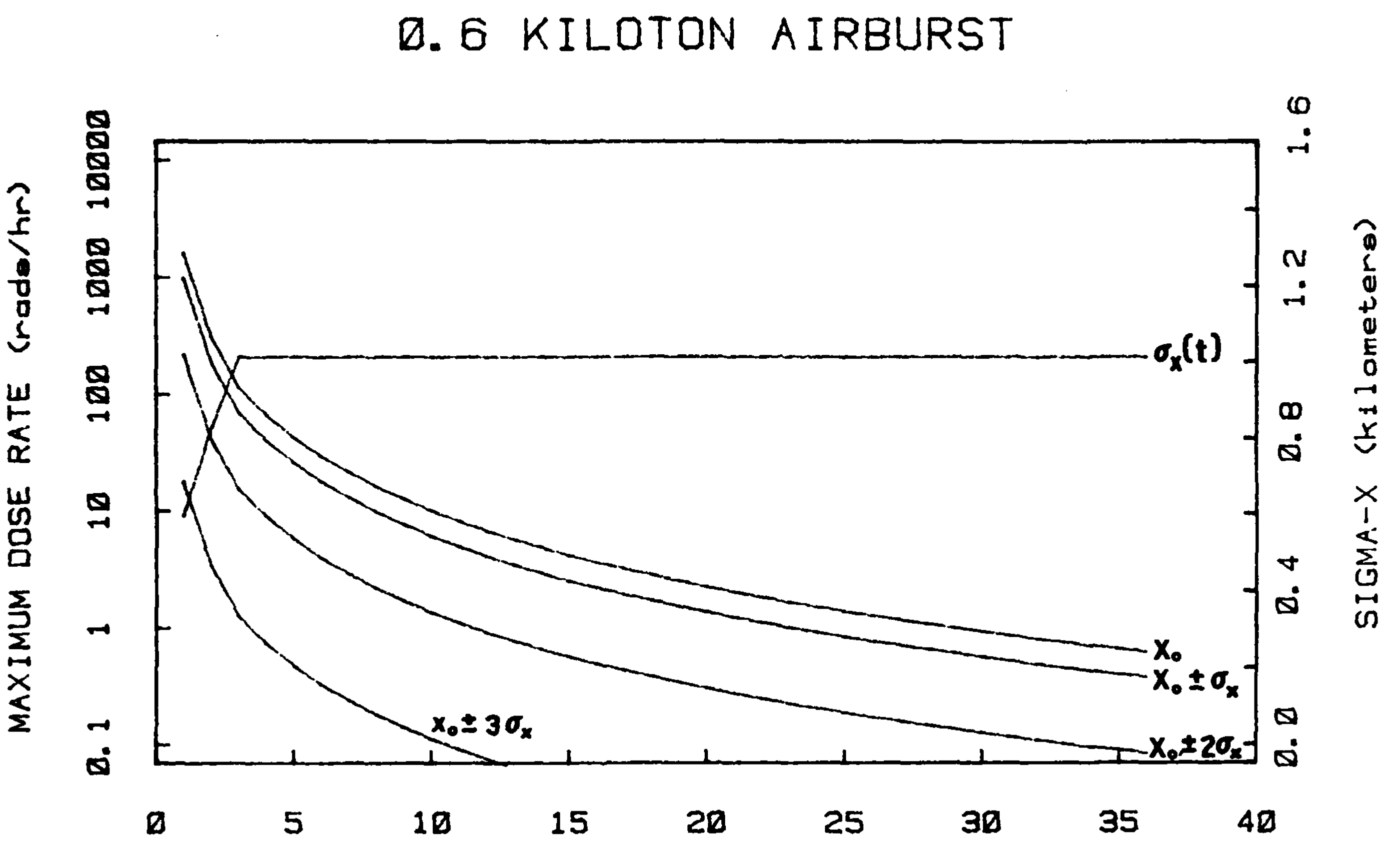

Figure 15. Maximum Dose Rate and Sigma-x Distance

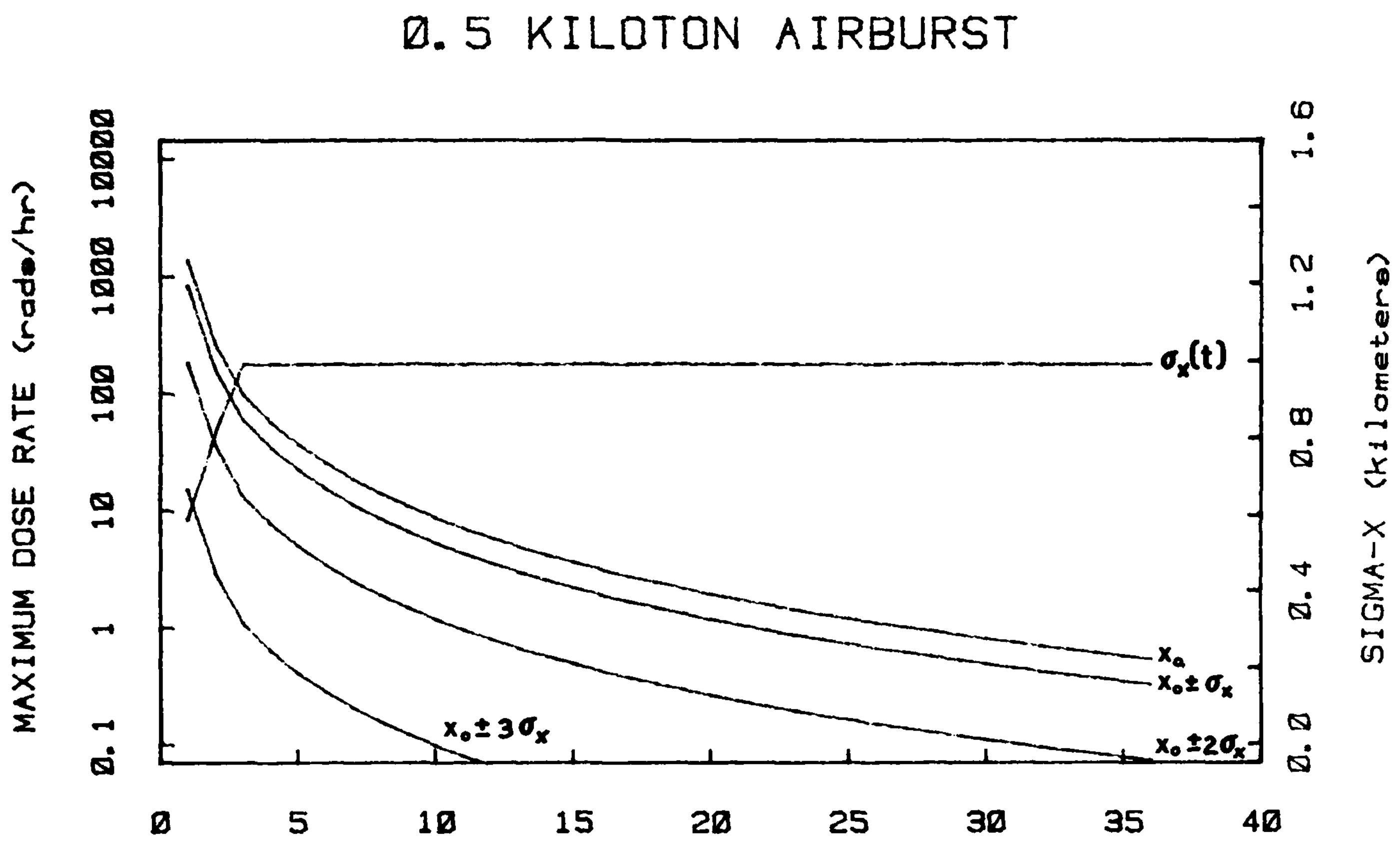

Figure 16. Maximum Dose Rate and Sigma-x Distance

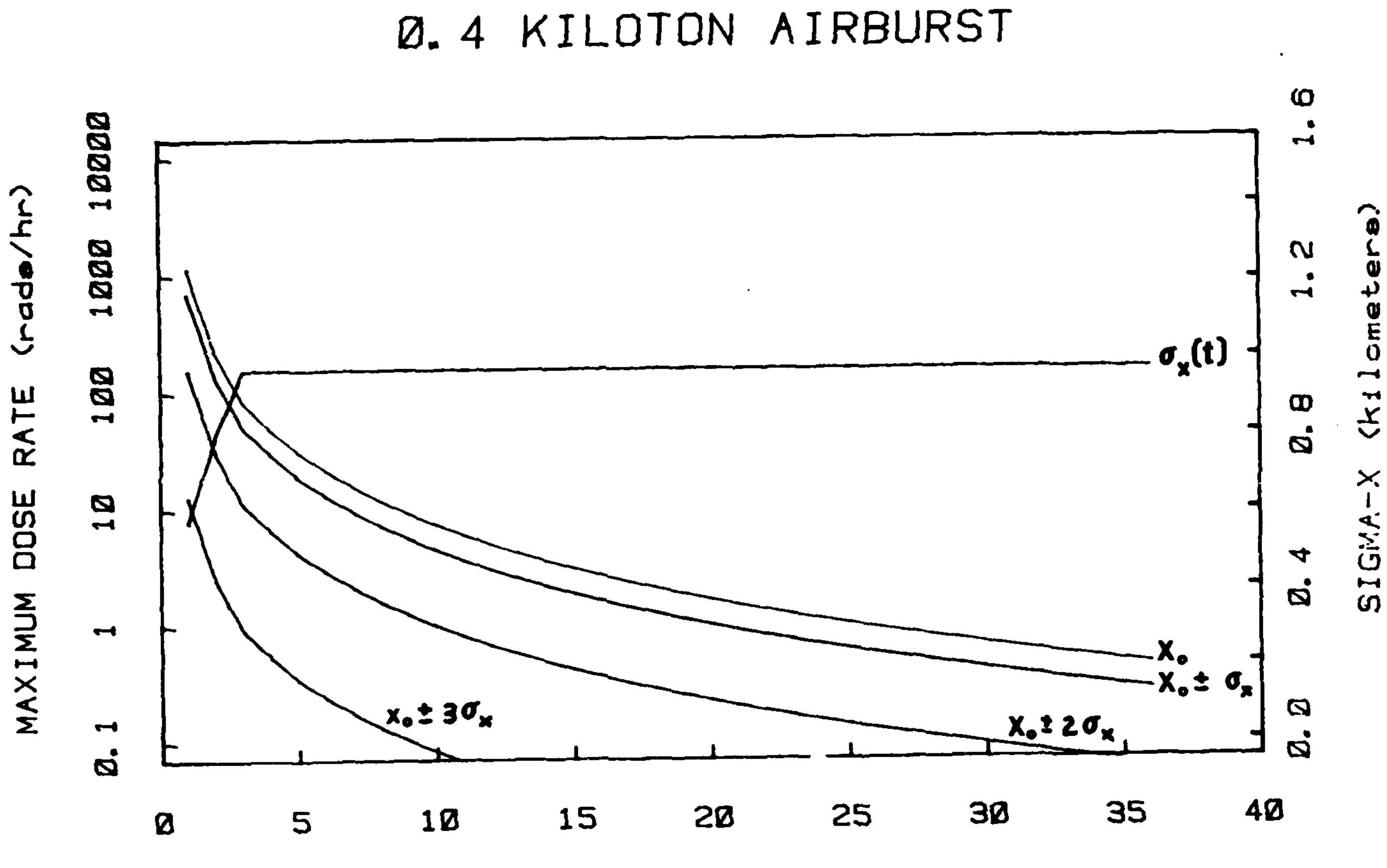

Figure 17. Maximum Dose Rate and Sigma-x Distance

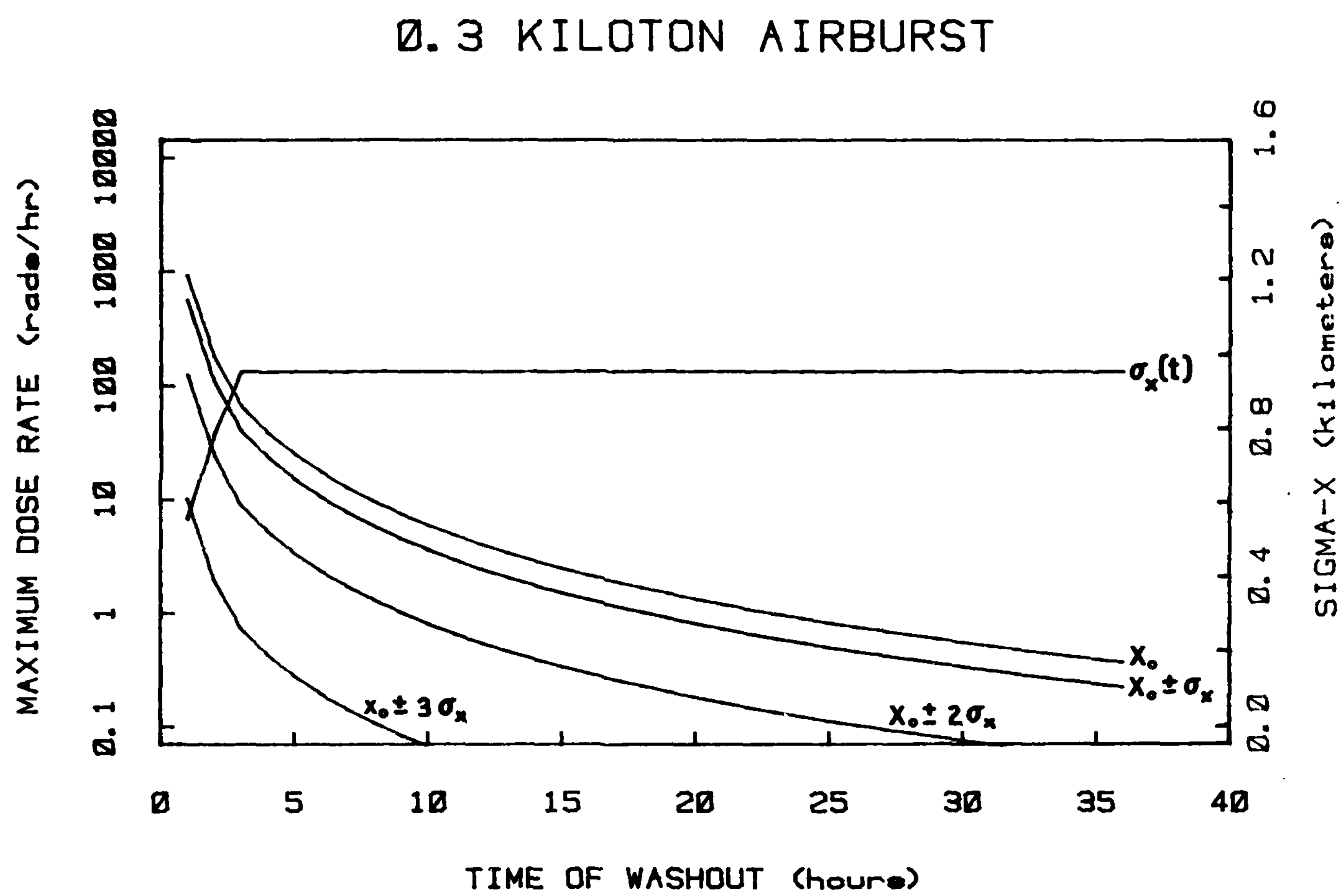

Figure 18. Maximum Dose Rate and Sigma-x Distance

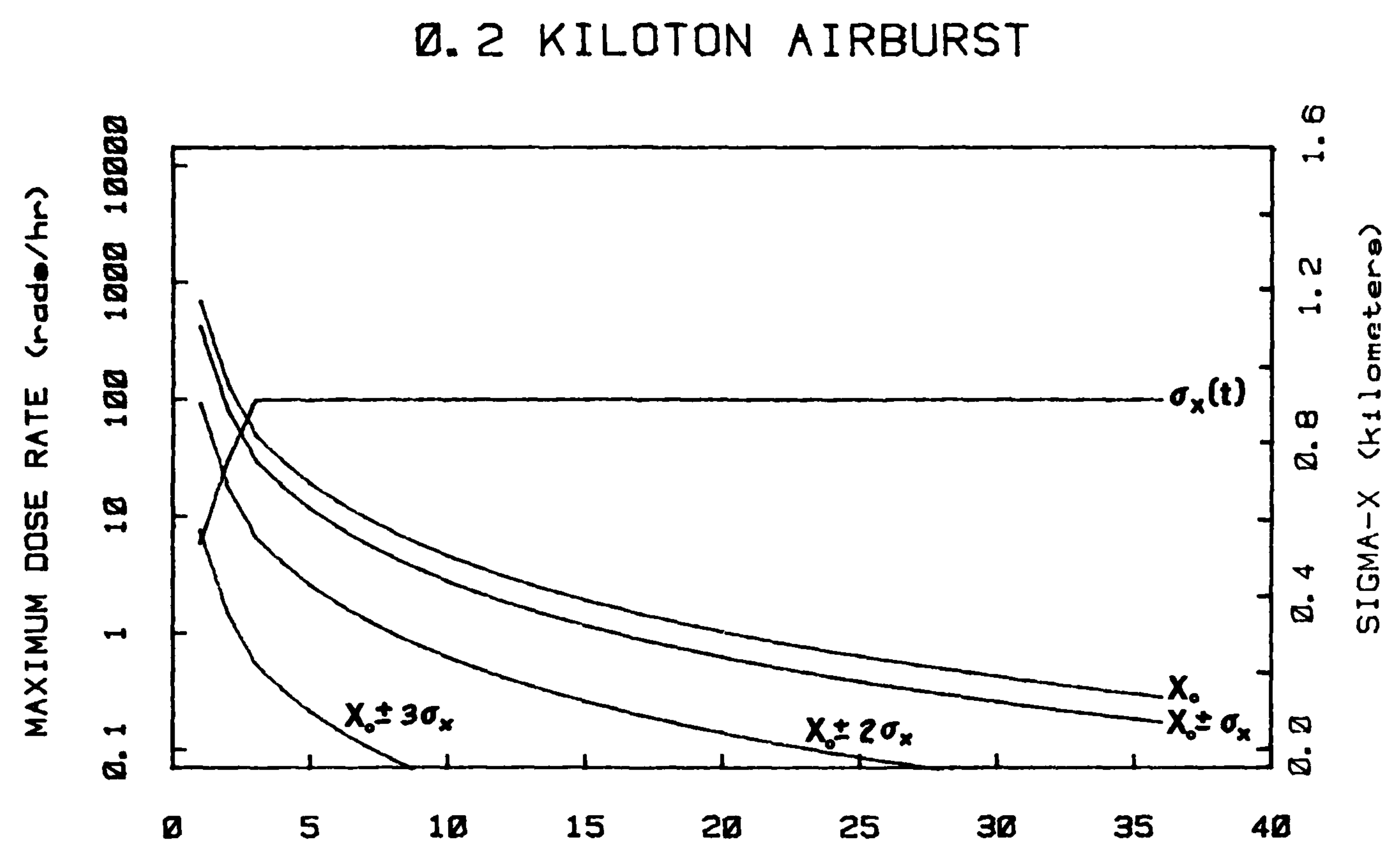

Figure 19. Maximum Dose Rate and Sigma-x Distance

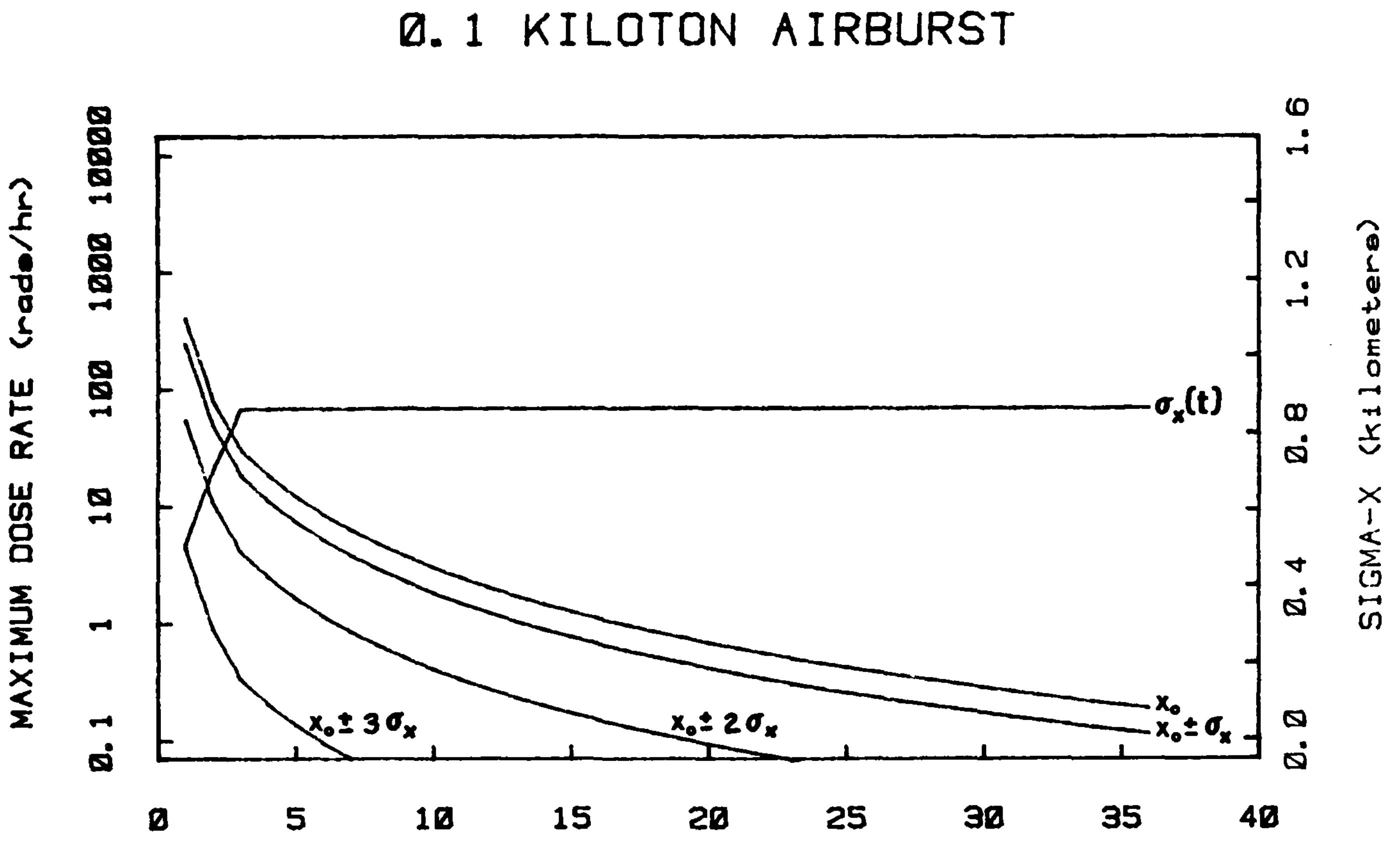

Figure 2Ø. Maximum Dose Rate and Sigma-x Distance

VI. Conclusions and Recommendations

Conclusions

Based on the results of this study, the following conclusions can be drawn.

a. Utility of the model is limited to weapon yields ranging between 0.01 kilotons to 1.0 kilotons. This results from the limited low yield visible cloud data available from atmospheric tests.

b. Fractional arrival rate of activity function, g(t), presently used in smearing codes, is a poor model for predicting airburst fallout.

c. The immersion dose resulting from an airburst is not significant as a ground threat.

d. Airburst fallout is only tactically significant through the mechanism of cloud scavenging up to 36 hours after cloud stabilization.

Recommendations

The rain scavenging model provides a useful airburst fallout prediction tool; however, there is room for improvement. The following recommendations would be appropriate for future study and are hereby offered.

a. Compile a larger cloud data base with the intent of developing a single yield dependent cloud center height relation useful from sub-kiloton to megaton yields.

b. Incorporate a raindrop size distribution into the model and begin the fallout deposition process at the time rainfall begins. The intent is to compute a raindrop activity deposition function, g(t).

c. Develop a method of predicting and using a "mean particle attachment rate" of fallout particles to raindrops. This could be used to modify the raindrop $g(t)$ function.

Appendix A

Conversion of the Ground Activity Distribution per Unit Area to a Dose Rate

The ground distribution of activity per unit area, A(x,y,t) in curies/m², can be converted to a dose rate in Rads/hr at a detector 3 feet off the ground. This is accomplished by doing a point kernal integration of the gamma ray sources within the fallout field grounded about a position having coordinates x and y at a given time t (Ref 3:207). The geometry used for this integration is illustrated in Figure 21.

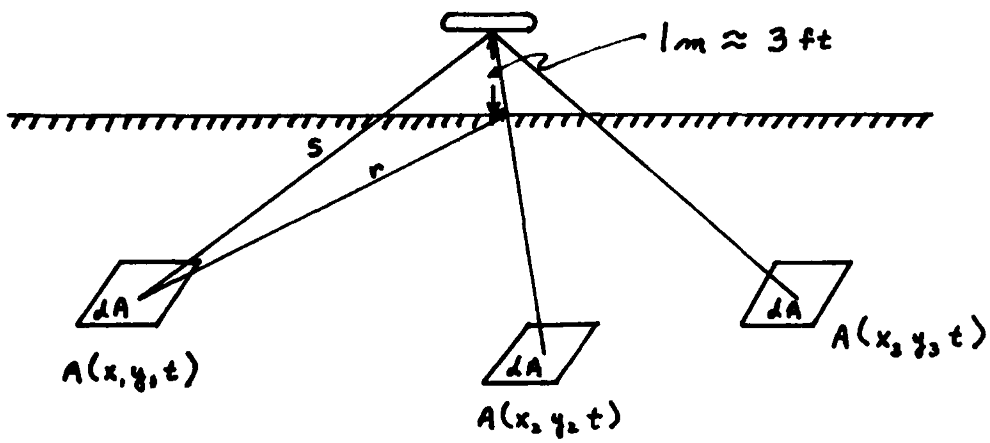

Figure 21. Point Kernal Integration Geometry

The gamma ray sources are represented as point emitters located at points of equal differential area dA. It is assumed that the spatial variation in A(x,y,t) away from the detector is small in terms of gamma mean free paths. By making this assumption, the spatial variation in

A(x,y,t) can be ignored and the integration taken to infinity. Additionally, the gamma ray photons under go absorption by air molecules, are spherically attenuated as distance away from the detector increases, and are attenuated by one other absorbing media, namely the detector. The exposure rate at ground position x, y and at time t can now be represented by

$$\dot{D}(x,y,t) = \int_{o}^{\infty} A(x,y,t) \left(\frac{\mu_a}{\rho}\right) C_1 \left(\frac{C_2}{C_3}\right) \frac{e^{-\mu_t s}}{4\pi r^2} dA \qquad \text{(A-1)}$$

where

$\dot{D}(x,y,t)$ = Exposure rate at time t (roentgens/hr)

$A(x,y,t)$ = Ground distribution of activity ($curies/m^2$)

$\left(\frac{\mu_a}{\rho}\right)$ = Mass absorption coefficient for air (m^2/kg)

μ_t = Total absorption coefficient of the detector (m^{-1})

s = Distance from point emitter to detector (m)

C_1 = 3.7×10^{10} disintegrations/sec-curie

C_2 = 1.6×10^{-13} joules/disintegration

C_3 = 0.00877 joules/kg-roentgen

By substituting $dA = 2\pi r dr$, assuming the average gamma ray photon energy to be 1 MeV, and using $\left(\frac{\mu_a}{\rho}\right) = 0.0028\ m^2/kg$ (Ref 7:713), equation (A-1) reduces to

$$\dot{D}(x,y,t) = 3.4A(x,y,t) \int_{o}^{\infty} \frac{e^{-\mu_t s}}{s^2} r dr \qquad \text{(A-2)}$$

where the dimensions on the constant are in roentgens per hour per unit activity per unit area.

The above integral can be simplified further. The geometry in Figure 21 yields:

$$s^2 = (1m)^2 + r^2 \qquad \text{(A-3)}$$

Differentiating both sides, substituting into the integral, and redefining integration limits gives:

$$\int_0^\infty \frac{e^{-\mu_t s}}{s^2}\, r\,dr = \int_1^\infty \frac{e^{-\mu_t s}}{s}\, ds \qquad \text{(A-4)}$$

Now, let:

$$\mu_t s = z \qquad \text{(A-5)}$$

and

$$\frac{ds}{s} = \frac{dz}{z} \qquad \text{(A-6)}$$

Substituting into equation (A-4) and simplifying gives:

$$\int_0^\infty \frac{e^{-\mu_t s}}{s^2}\, r\,dr = \int_{\mu_t}^\infty \frac{e^{-z}}{z}\, dz \qquad \text{(A-7)}$$

The integral on the right hand side of equation (A-7) is now in the form of an Exponential Integral of the First Kind, $E_1(\mu_t)$. For air, the value of μ_t is taken to be 0.0082 m^{-1} (Ref 7:689). Substituting and using an approximation for E_1 (.0082) from Abramowitz and Stegun (Ref 1:231)

gives

$$\int_{.0082}^{\infty} \frac{e^{-z}}{z}\, dz \approx 4.23 \tag{A-8}$$

Substituting this result into equation (A-2) yields:

$$\dot{D}(x,y,t) = 14.4A(x,y,t) \tag{A-9}$$

This gives the exposure rate in roentgens per hour.

When computing the dose rate in rads per hour, the detector would be human tissue rather than air. Since human tissue is comprised mainly of water, the μ_t value of water can be used as an approximation. The value of the constant C_3 also changes to 0.01 joules/rad. The end result is approximately the same as equation (A-9). Equation (A-9) can then be used to convert a ground activity distribution per unit area to a dose rate in rads per hour.

Appendix B

Calculation of Atmospheric Dynamic Viscosity

The US Standard Atmosphere (Ref 17) provides empirical relations of atmospheric properties as functions of altitude. These relations have been fit to atmospheric data at various levels in the atmosphere.

The largest weapon yield utilized in this thesis is 1 kiloton. The cloud center height predicted by equation (5) for 1 kiloton is 2531 m. For calculating the dynamic viscosity of the atmosphere, it is only necessary to use the relations given for altitudes up to 11000 m.

The US Standard Atmosphere defines the dynamic viscosity as

$$\mu(T) = \frac{1.458 \times 10^{-6}\, T^{1.5}}{T + 110.4} \tag{B-1}$$

where T is the ambient temperature of the atmosphere in °K and μ is in kg/m-sec (Ref 17:19). The ambient atmospheric temperature in °K is expressed as a function of altitude by

$$T(z) = 288.15 - .0065z \tag{B-2}$$

where z is the altitude in m (Ref 17:10). By substituting equation (B-2) into equation (B-1), the dynamic viscosity of the atmosphere is computed directly from any given altitude up to 11000 m.

Appendix C

The Airburst Scavenging Model Program

The airburst scavenging model was written in Standard FORTRAN 77 and executed at the Air Force Institute of Technology computer facility on a DEC VAX-11/780 computer. This appendix contains the following:

I. Program Variable Listing

II. Listing of the Source Program

I. Program Variable Definitions

1. ALPHA0 = Parameter of the particle number size distribution: logarithm of the median particle radius.

2. ALPHA2 = Parameter of the surface activity-size distribution: logarithm of the median particle radius.

3. ALPHA3 = Parameter of the volumetric activity-size distribution: logarithm of the median particle radius.

4. AXYT = Ground distribution of activity per unit area (curies/m^2).

5. BETA0 = Logarithmic slope of the particle number-size distribution.

6. CODE = An integer code used for computing different doses: Code 0 for dose to infinity, code 1 for dose to 24 hours, code 2 for dose to 4 hours.

7. DDOT = Dose rate (Rads/hr).

8. DELTAT = Time step parameter set to 1.0 hours. It is used in the Stoke's Law fall mechanics.

9. DELTAZ = Distance fallout particles fall during time DELTAT (m).

10. EXPO = Dummy variable representing the exponential argument in the variable SIGO.

11. EXPOFX = Dummy variable representing the exponential argument in the variable FX.

12. EXPOFY = Dummy variable representing the exponential argument in the variable FY.

13. DOSE = Gamma radiation dose (Rads).

14. FV = Volumetric fractionation ratio.

15. FX = Normalized Gaussian distribution in the x direction.

16. FY = Normalized Gaussian distribution in the y direction.

17. GA = Acceleration due to gravity (9.80 m/sec^2).

18. HC = Stabilized cloud center height (m).

19. MU = Dynamic viscosity (kg/m-sec).

20. NUMBER = Dummy variable representing the squared value of SIGY.

21. PI = The mathematical constant π.

22. RHOP = Mass density of fallout particles (kg/m^3).

23. RMEAN = Vector specifying the values of mean particle radii in each of the 10 equal activity-size groups (microns).

24. SHEARX = Wind shear in the x direction (km/hr-km).

25. SHEARY = Wind shear in the y direction (km/hr-km).

26. SIGO = Standard deviation of horizontal cloud radius (m).

27. SIGX = Cloud standard deviation in the x direction (m).

28. SIGY = Cloud standard deviation in the y direction (m).

29. SIGZ = Cloud standard deviation in the vertical direction (m).

30. TC = WSEG time constant (hours).

31. TEMP = Ambient atmospheric temperature (°K).

32. TIME = Time of cloud washout (hours).

33. TSTAR = WSEG toroidal growth time of cloud (hours).

34. UTRD = Unit time reference dose rate (Rads/hr).

35. V = Fallout particle fall velocity (m/sec).

36. VX = Wind velocity in the x-direction (m/sec).

37. VY = Wind velocity in the y-direction (m/sec).

38. XO = Cloud center position in the x-direction (m).

39. X = Distance east/west of XO (m).

40. YO = Cloud center position in the y-direction (m).

41. Y = Distance north/south of YO (m).

42. YIELD = Weapon yield (kilotons).

43. ZC = Two-dimensional array of particle size group center altitudes at different times of fall.

II. Listing of the Source Program

```
************************************************************************
*                                                                      *
*                           RAINOUT MODEL                              *
*                                                                      *
*                                                                      *
*   This program computes the maximum dose rate, in Rads per hour,     *
*   produced by a nuclear air burst. The nuclear cloud is washed out by a *
*   simulated rain storm at a specified time t of cloud washout. The   *
*   activity grounded as a result of the radioactive cloud washout,    *
*   A(x,y,t), is used to compute the dose rate. This program will accomo- *
*   date changes in the following input parameters: particle size dist- *
*   ribution, weapon yield (for yields ranging from .Ø1 to 1.Ø kilotons), *
*   fractionation ratio, fallout particle density (in kilograms per cubic *
*   meter),wind velocity (in meters per second), and wind shear (in    *
*   kilometers per hour per kilometer of atmospheric altitude).        *
*                                                                      *
************************************************************************

      REAL PI,ALPHAØ,BETAØ,FV,RHOP,GA,RMEAN(1Ø),YIELD,HC,ALPHA2,ALPHA3
      REAL TEMP,MU,DELTAZ,VPRINT,XØ,YØ,AXYT,DDOT(4),DOSE(4)
      REAL V,SIGMAZ(1Ø),DELTAT,ZC(1Ø,Ø:5Ø),TIME(Ø:5Ø),UTRD(4)
      REAL TC,SIGZ,SIGØ,EXPO,SIGX,TSTAR,SIGY,NUMBER,SHEARX,SHEARY,VX,VY
      REAL X(4),Y,FX,FY,EXPOFX,EXPOFY
      INTEGER I,J,K,CODE,K1

C   INPUT OF ALL PROBLEM PARAMETERS.

      PARAMETER (PI=3.14159, ALPHAØ=LOG(.Ø75), BETAØ=LOG(2.Ø), FV=1.Ø,
     +           RHOP=55ØØ.Ø, GA=9.8Ø, YIELD=Ø.1, VX=4.Ø, VY=Ø.Ø,
     +           SHEARX=1Ø.Ø, SHEARY=1.Ø, Y=Ø.Ø, CODE=Ø )

      OPEN (3,FILE='dosedata')
      REWIND 3

C   SPECIFY THE MEAN PARTICLE RADII FOR THE TEN EQUAL ACTIVITY GROUPS.

      CALL MEAN(ALPHAØ,BETAØ,ALPHA2,ALPHA3,RMEAN)

C   COMPUTE THE ALTITUDE OF THE STABILIZED CLOUD CENTER IN METERS.

      HC=(16Ø9./5.28)*(8.3Ø476298+.63632921*LOG(YIELD)-.39763749*LOG(YIE
     +LD)*LOG(YIELD)-.Ø1364Ø81*LOG(YIELD)**3+.ØØ56Ø846*LOG(YIELD)**4)
      TC=(12.*(HC/6Ø.)*(5.28/16Ø9.)-2.5*(HC/6Ø.)*(5.28/16Ø9.)*(5.28/16Ø9
     +    .))*(1.Ø-.5*EXP((HC/25.)*(5.28/16Ø9.)*(5.28/16Ø9.)))
      SIGZ=.18*HC
      EXPO=.7+(1./3.)*LOG(YIELD/1ØØØ.)-(3.25/(4.+(LOG(YIELD/1ØØØ.)+5.4)
     +     *(LOG(YIELD/1ØØØ.)+5.4)))
      SIGØ=16Ø9.*EXP(EXPO)

      PRINT 1, YIELD
    1 FORMAT (/,"YIELD = ",F6.4," KILOTON AIRBURST")
      PRINT 2, HC
    2 FORMAT (/,"STABILIZED CLOUD CENTER HEIGHT = ",F5.Ø," METERS")
      PRINT 25, TC
   25 FORMAT (/,"TC = ",F5.2," HOURS")
      PRINT 26, SIGØ
   26 FORMAT (/,"SIGMAØ = ",F5.Ø," METERS")
      PRINT 27, SIGZ
   27 FORMAT (/,"SIGMAZ = ",F4.Ø," METERS")
      PRINT 28, VX
   28 FORMAT (/,"DOWNWIND VELOCITY = ",F4.1," METERS PER SECOND")
      PRINT 3, FV
```

```
  3 FORMAT (/,"VOLUMETRIC FRACTIONATION RATIO = ",F4.2)
    PRINT 35, RHOP
 35 FORMAT (/,"PARTICLE MASS DENSITY = ",F5.Ø," KILOGRAMS PER CUBIC ME
   +TER")
    PRINT 4, ALPHAØ,BETAØ
  4 FORMAT (/,"ALPHAØ = LN(.Ø75) = ",F6.3,"     BETAØ = LN(2.Ø) = ",
   +F5.3)
    PRINT 5, ALPHA2,ALPHA3
  5 FORMAT (/,"ALPHA2 = LN(.196) = " F6.3,"    ALPHA3 = LN(.317) = "
   +,F6.3,//)

C   COMPUTE THE ALTITUDE FOR THE CENTER OF EACH PARTICLE SIZE GROUP.

    DO 7 I=1,1Ø
       ZC(I,Ø)=HC
       SIGMAZ(I)=.18*ZC(I,Ø)
  7 CONTINUE

C   COMPUTE THE FALL TIMES FOR EACH SIZE GROUP CENTER USING STOKE'S LAW
C   FALL MECHANICS.

    TIME(Ø)=Ø.Ø
    DELTAT=1.Ø
    DO 13 J=1,36
       TIME(J)=TIME(J-1)+DELTAT
       DO 12 I=1,1Ø
          DELTAT=DELTAT*36ØØ.Ø
          TEMP=288.15-.ØØ65*ZC(I,J-1)
          MU=(1.458E-6*TEMP**1.5)/(TEMP+11Ø.4)
          V=(2.Ø/9.Ø)*((RMEAN(I)*1E-6)**2*RHOP*GA)/MU
          DELTAZ=V*DELTAT
          ZC(I,J)=ZC(I,J-1)-DELTAZ
          IF(ZC(I,J).LT.Ø.Ø)THEN
             ZC(I,J)=Ø.Ø
             GO TO 1Ø5
          END IF
1Ø5       DELTAT=DELTAT/36ØØ.Ø
          VPRINT=V*1ØØ.Ø
 12    CONTINUE
 13 CONTINUE

C   COMPUTE THE VALUE OF THE DOSE RATE IN R/hr.

    IF(CODE.EQ.Ø)THEN
       PRINT*,' '
       PRINT*,'DOWNWIND      SIGMAX       TIME OF                  DOSE
   + TO'
       PRINT*,'DISTANCE     DISTANCE      WASH OUT    DOSE RATE    INFI
   +NITY'
       PRINT*,'  (Km)         (Km)         (hours)    (Rads/hr)     (Ra
   +ds)'
       PRINT*,' '
       GO TO 2ØØ
       ELSE IF(CODE.EQ.1)THEN
          PRINT*,' '
          PRINT*,'DOWNWIND      SIGMAX       TIME OF                  D
   +OSE TO'
          PRINT*,'DISTANCE     DISTANCE      WASH OUT   DOSE RATE     2
   +4 HOURS'
          PRINT*,'  (Km)         (Km)         (hours)   (Rads/hr)
   +(Rads)'
          PRINT*,' '
          GO TO 2ØØ
                              ELSE
```

```
         PRINT*,' '
         PRINT*,'DOWNWIND     SIGMAX       TIME OF
     +DOSE TO'
         PRINT*,'DISTANCE    DISTANCE      WASH OUT   DOSE RATE
     +4 HOURS'
         PRINT*,'  (Km)        (Km)         (hours)   (Rads/hr)
     +(Rads)'
         PRINT*,' '
         GO TO 200
      END IF

  200 DO 17 J=1,36
         IF(TIME(J).LE.3.0)THEN
            TSTAR=TIME(J)
            GO TO 135
         END IF
         TSTAR=3.0
  135    SIGX=SIG0*SQRT(1.0+8.0*TSTAR/TC)
         NUMBER=SIG0*SIG0*(1.0+8.0*TSTAR/TC)+(SIGZ*SHEARY*TIME(J))*
     +           (SIGZ*SHEARY*TIME(J))
         SIGY=SQRT(NUMBER)
         X0=VX*TIME(J)*3600.0
         Y0=VY*TIME(J)*3600.0
         DO 14 K=1,4
         X(K)=X0+(K-1)*SIGX
         EXPOFX=-.5*((X(K)-X0)/SIGX)*((X(K)-X0)/SIGX)
         EXPOFY=-.5*((Y-Y0)/SIGY)*((Y-Y0)/SIGY)
         FX=(1.0/(SQRT(2.0*PI)*SIGX))*EXP(EXPOFX)
         FY=(1.0/(SQRT(2.0*PI)*SIGY))*EXP(EXPOFY)
         AXYT=(530.E6*YIELD*TIME(J)**(-1.2))*FX*FY
         DDOT(K)=14.4*AXYT
         UTRD(K)=DDOT(K)*TIME(J)**1.2
         IF(CODE.EQ.0)THEN
           DOSE(K)=5.0*UTRD(K)*TIME(J)**(-.2)
           GO TO 14
           ELSE IF(CODE.EQ.1)THEN
                   DOSE(K)=5.0*UTRD(K)*(TIME(J)**(-.2)-(TIME(J)+24.0)**
     +                     (-.2))
                   GO TO 14
                             ELSE
                   DOSE(K)=5.0*UTRD(K)*(TIME(J)**(-.2)-(TIME(J)+4.0)**
     +                     (-.2))
                   GO TO 14
         END IF
   14    CONTINUE
         SIGX=SIGX/1000.0
         WRITE (3,136,IOSTAT=K1,ERR=17) TIME(J),DDOT(1),DDOT(2),DDOT(3),
     +   DDOT(4),DOSE(1),DOSE(2),DOSE(3),DOSE(4),SIGX
  136    FORMAT (F4.1,1X,E11.6,1X,E11.6,1X,E11.6,1X,E11.6,1X,E11.6,1X,
     +   E11.6,1X,E11.6,1X,E11.6,1X,F8.2)
         PRINT 15, X,SIGX,TIME(J),DDOT,DOSE
   15    FORMAT (F8.3,4X,F8.3,9X,F4.1,7X,F7.2,5X,F8.2)
   17 CONTINUE
      ENDFILE (3)
      CLOSE (3)
      END

*************************************************************************
*                                                                       *
*                   SUBROUTINE FOR MEAN PARTICLE RADII                  *
*                                                                       *
*************************************************************************
```

```
      SUBROUTINE MEAN(ALPHAØ,BETAØ,ALPHA2,ALPHA3,RMEAN)
      REAL ALPHAØ,BETAØ,ALPHA2,ALPHA3,Z(1Ø),RMEAN(1Ø)
      INTEGER I
      DATA (Z(I),I=1,1Ø)/-1.64,-1.Ø3,-.672,-.384,-.126,.126,.384,.672,
     +1.Ø3,1.64/
      ALPHA2=ALPHAØ+2.Ø*BETAØ*BETAØ
      ALPHA3=ALPHAØ+3.Ø*BETAØ*BETAØ
      DO 1Ø I=1,1Ø
         RMEAN(I)=EXP(Z(I)*BETAØ+ALPHA3)
   1Ø CONTINUE
      RETURN
      END
```

Appendix D

Infinite Dose Calculations

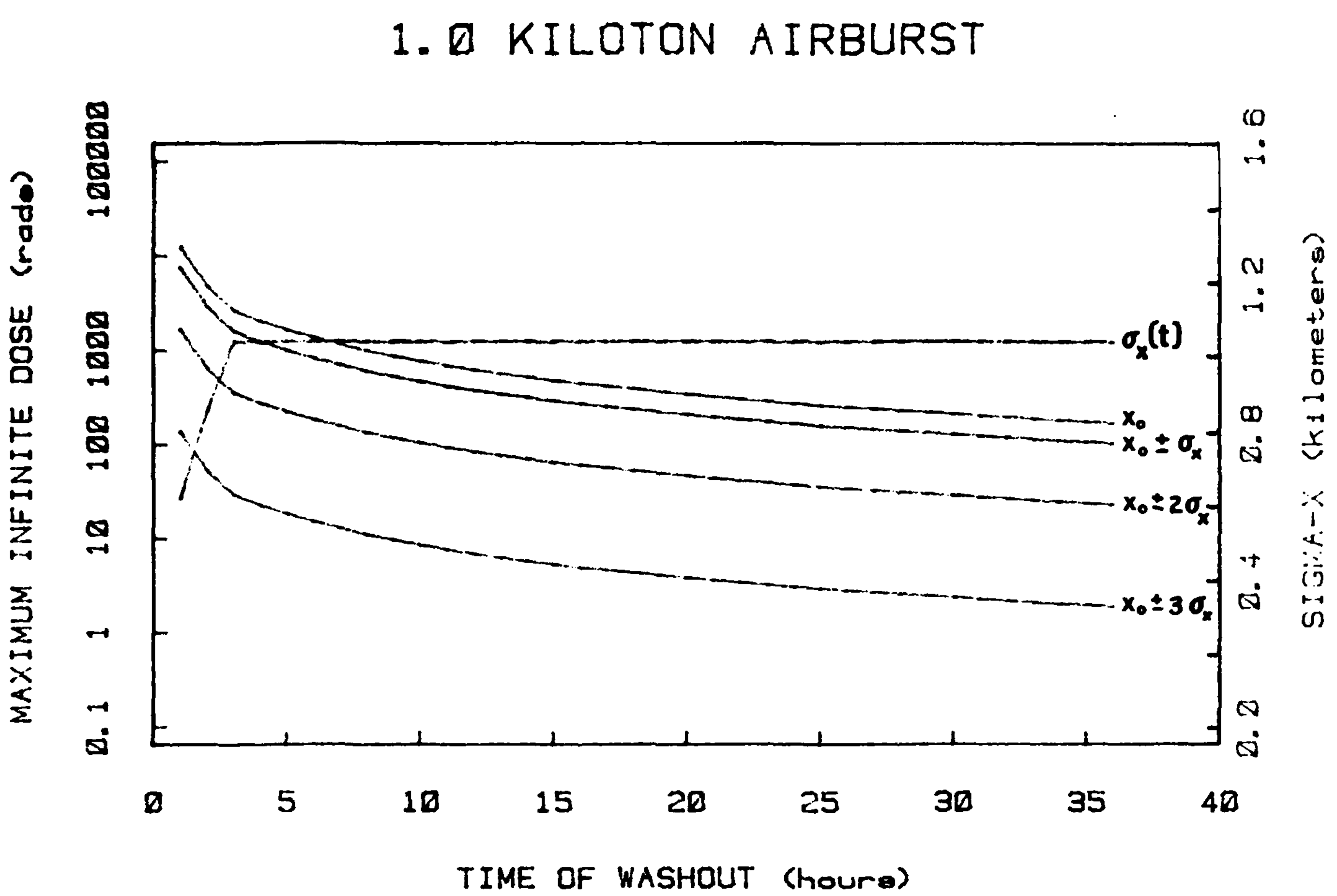

Figure 22. Maximum Infinite Dose and Sigma-x Distance

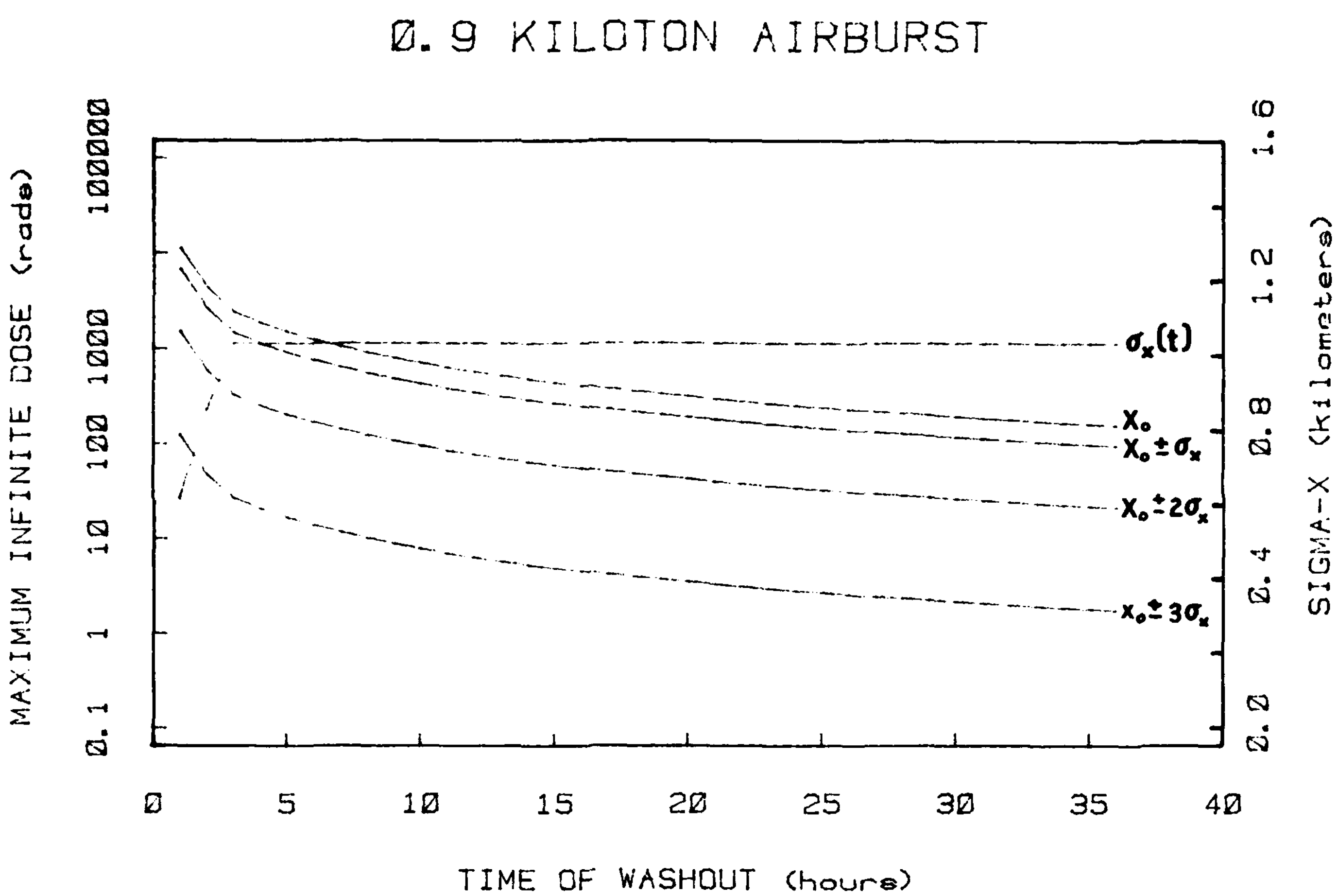

Figure 23. Maximum Infinite Dose and Sigma-x Distance

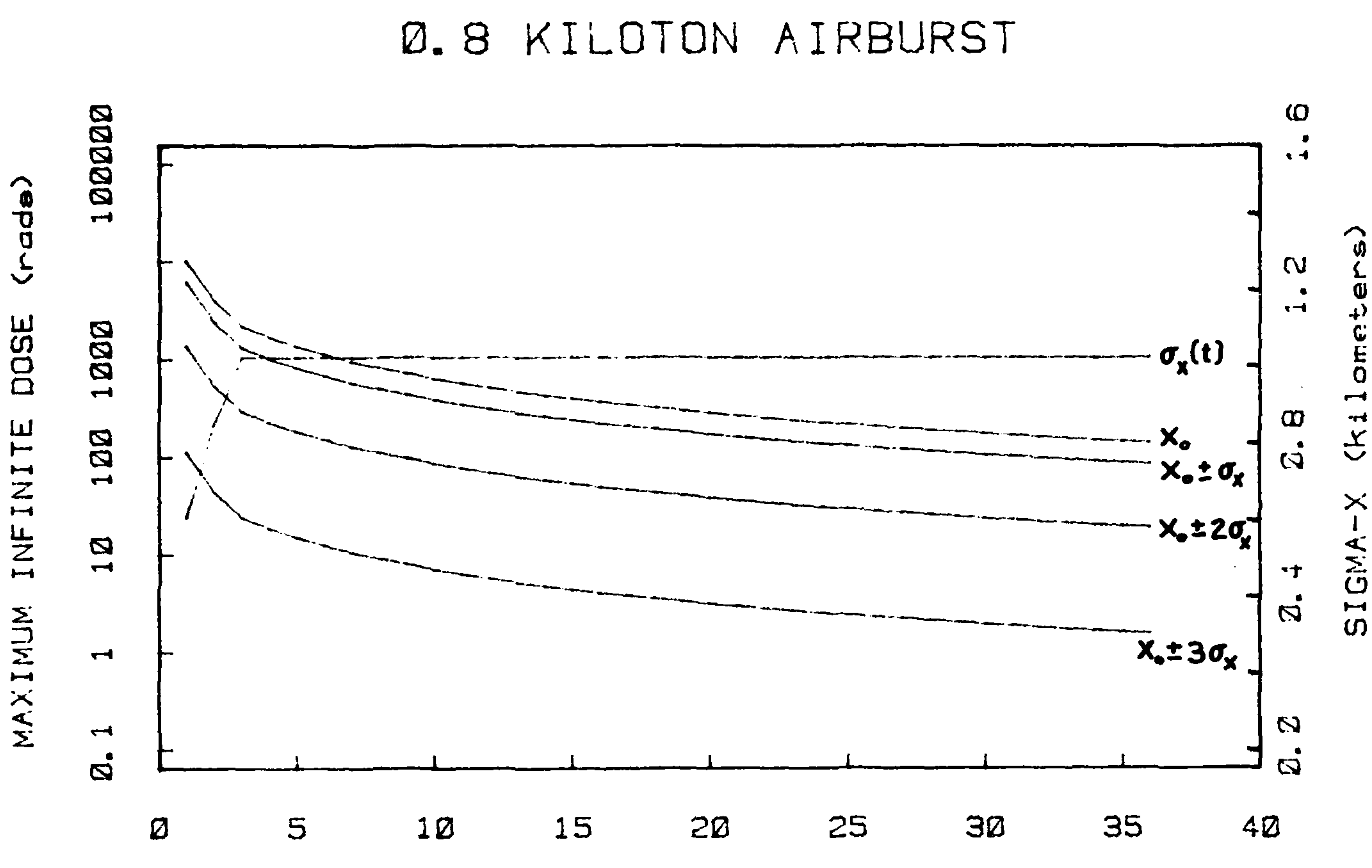

Figure 24. Maximum Infinite Dose and Sigma-x Distance

Ø.7 KILOTON AIRBURST

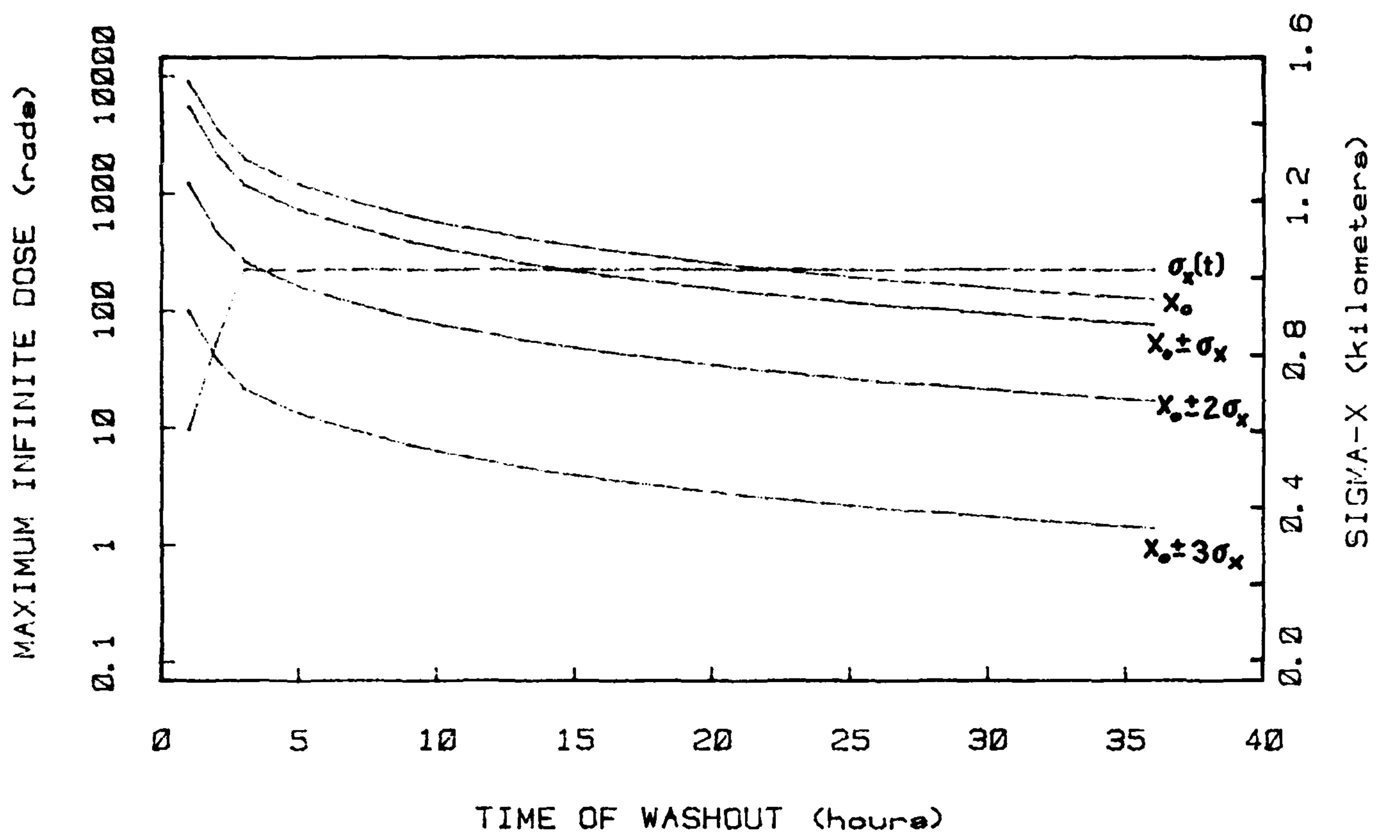

Figure 25. Maximum Infinite Dose and Sigma-x Distance

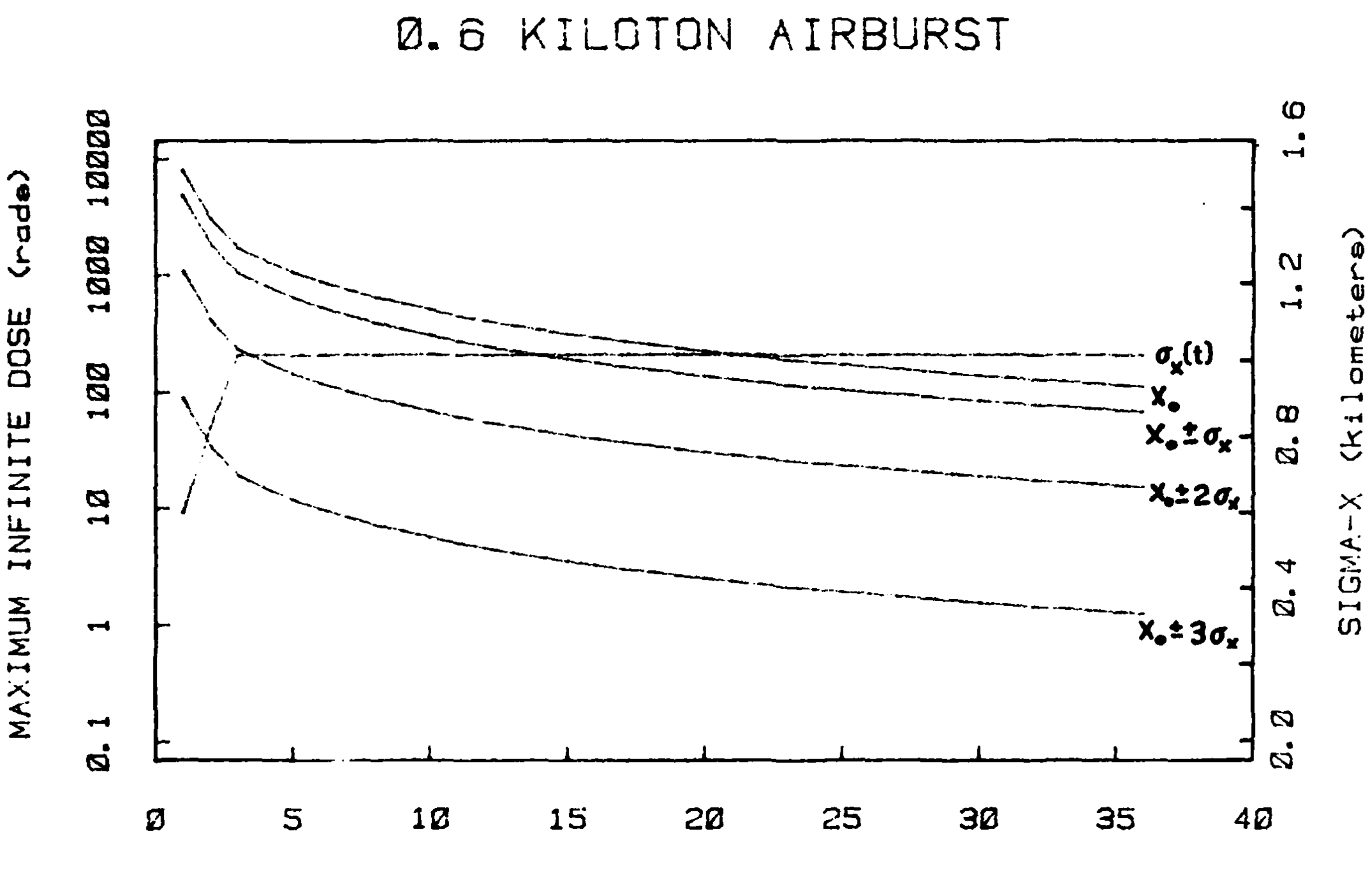

Figure 26. Maximum Infinite Dose and Sigma-x Distance

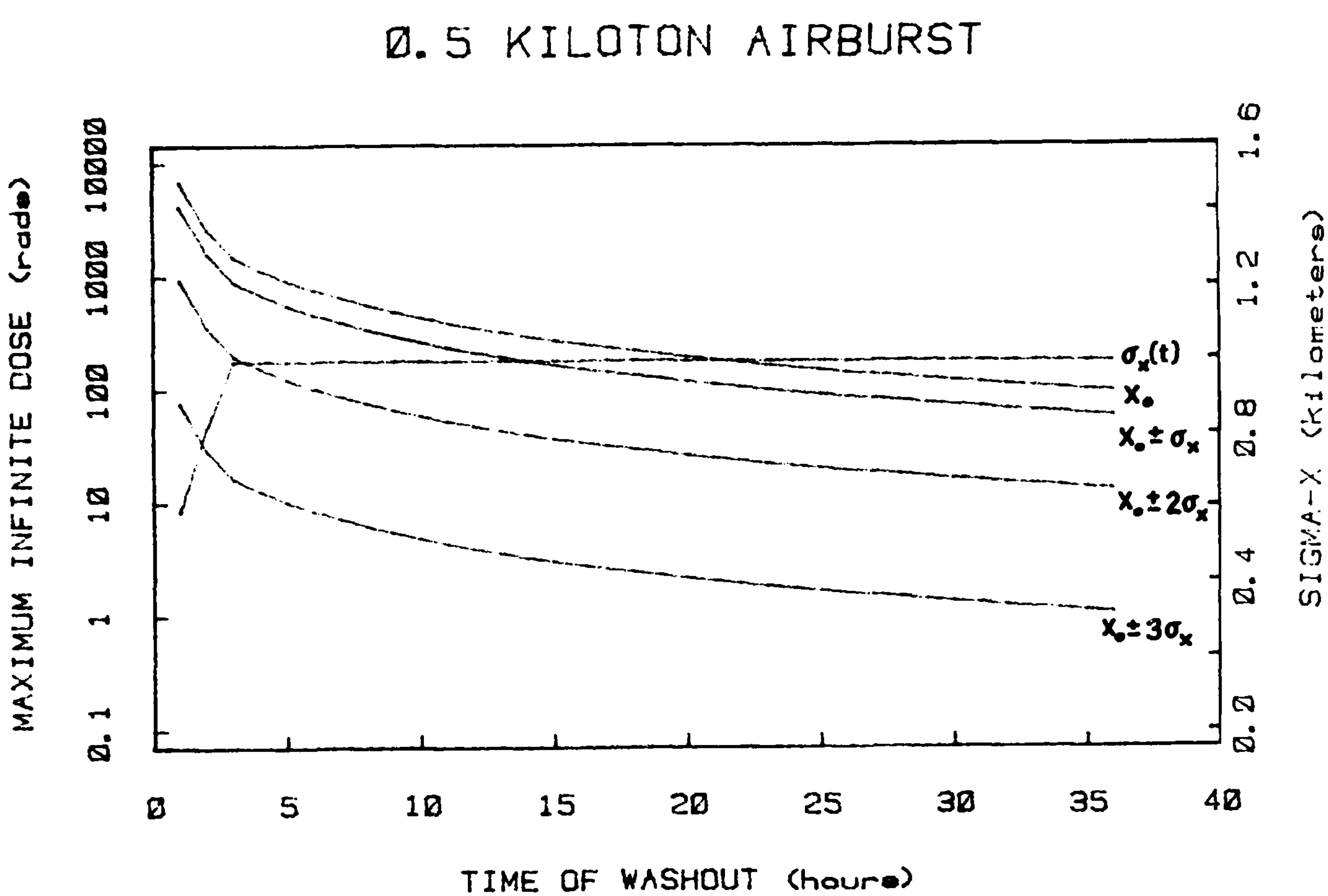

Figure 27. Maximum Infinite Dose and Sigma-x Distance

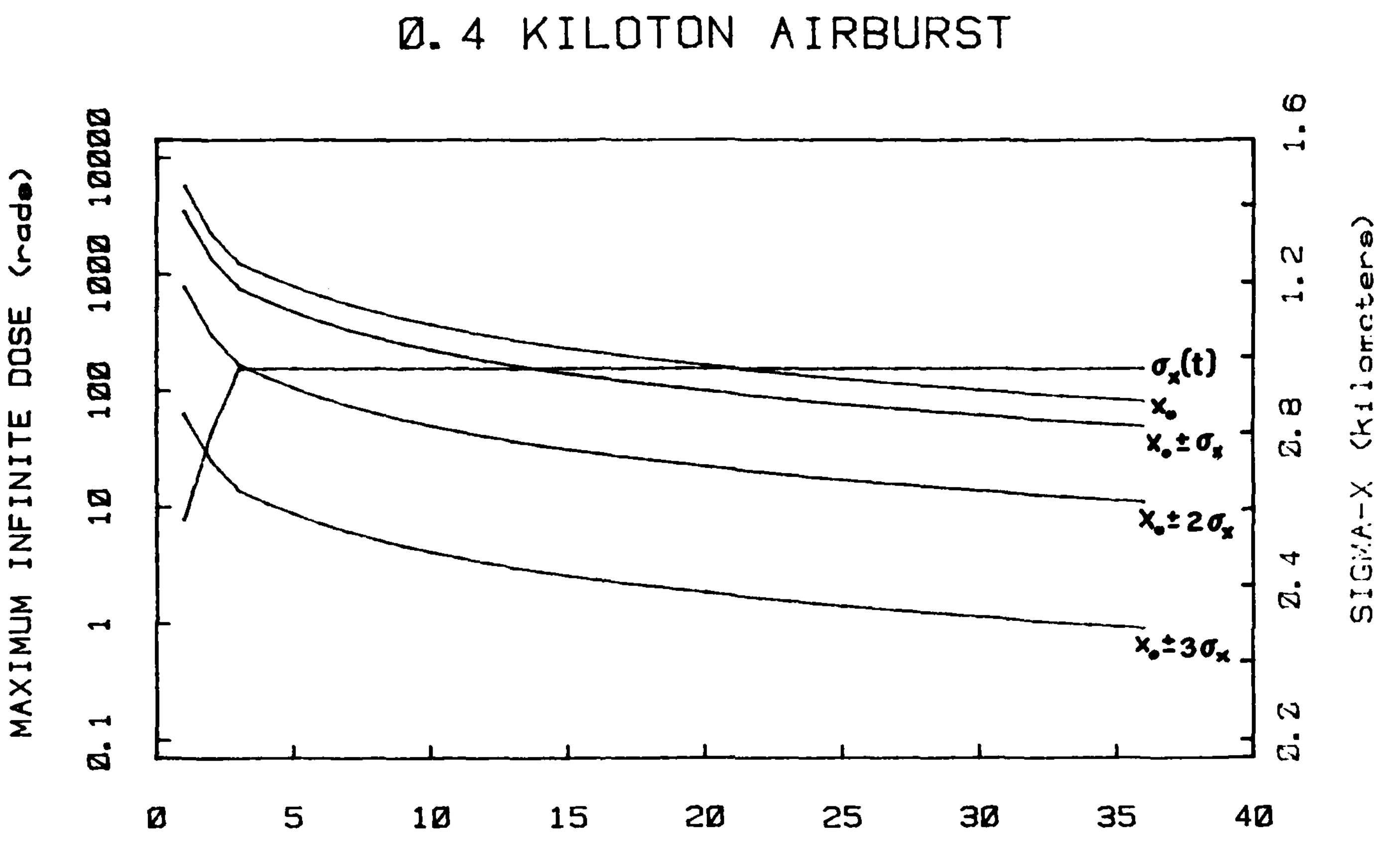

Figure 28. Maximum Infinite Dose and Sigma-x Distance

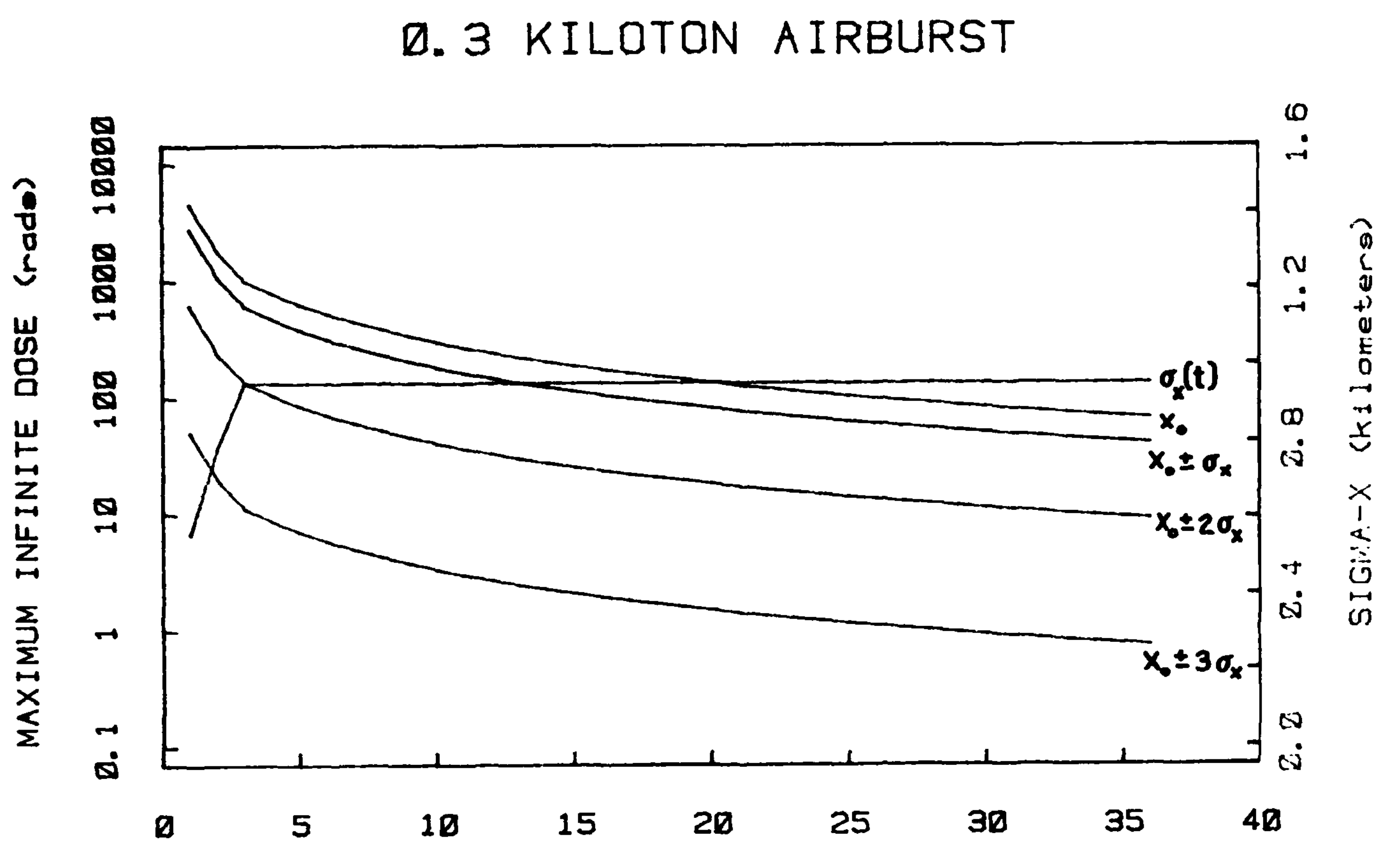

Figure 29. Maximum Infinite Dose and Sigma-x Distance

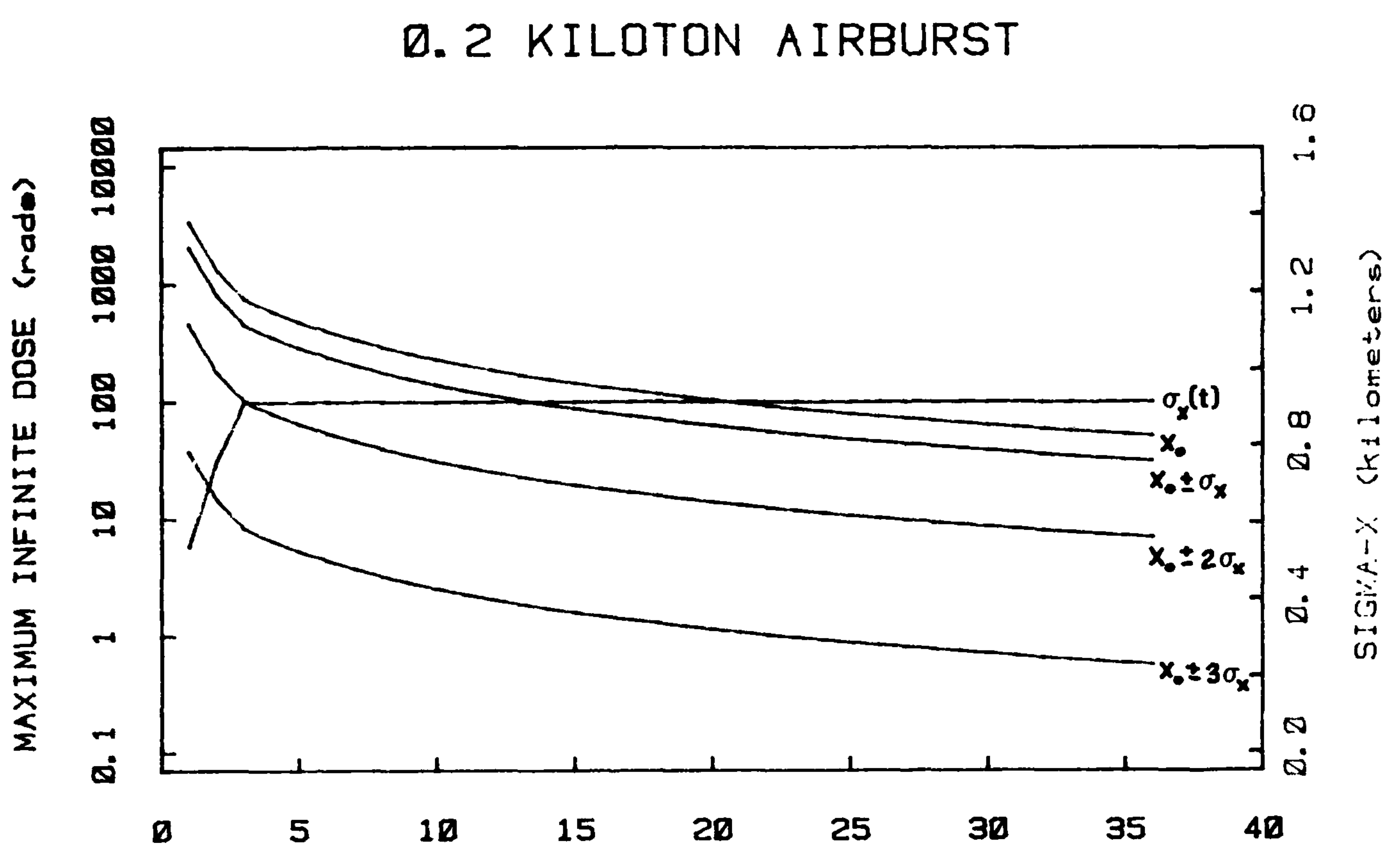

Figure 30. Maximum Infinite Dose and Sigma-x Distance

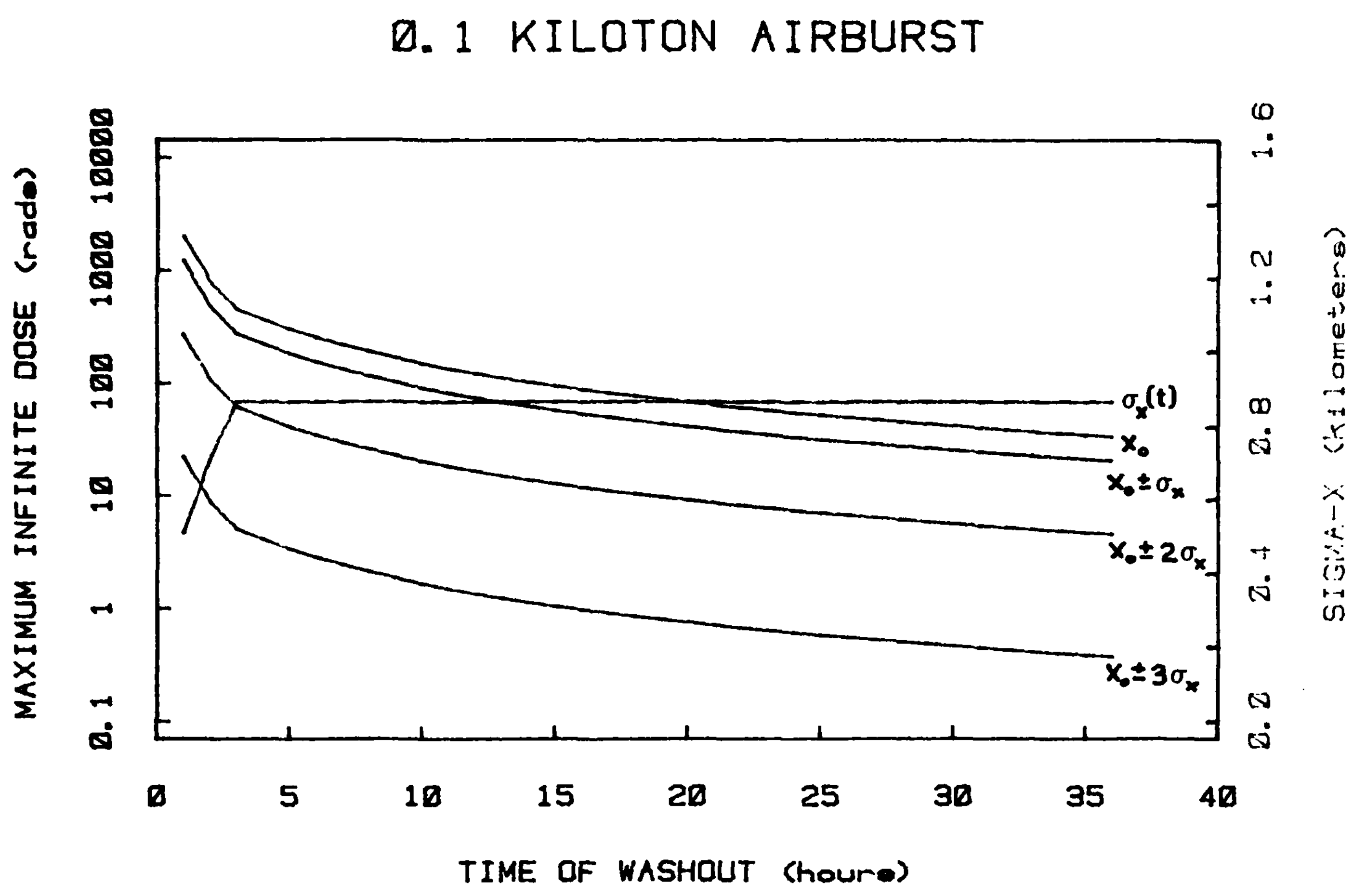

Figure 31. Maximum Infinite Dose and Sigma-x Distance

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AFIT/GNE/PH/84M-9	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION School of Engineering	6b. OFFICE SYMBOL (If applicable) AFIT/EN
7a. NAME OF MONITORING ORGANIZATION	
6c. ADDRESS (City, State and ZIP Code) Air Force Institute of Technology Wright-Patterson AFB, Ohio 45433	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State and ZIP Code)	10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.

11. TITLE (Include Security Classification)
See Box 19

12. PERSONAL AUTHOR(S)
Curtis R. Krieser, Capt, USA

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
MS Thesis	FROM ______ TO ______	1984 March	79

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB. GR.
15	02	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Fallout, Airburst, Nuclear Weapon Debris, Rainfall, Mathematical Models, Tactical Nuclear Weapons

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Title: A RAIN SCAVENGING MODEL FOR PREDICTING LOW YIELD AIRBURST WEAPON FALLOUT FOR OPERATIONAL TYPE STUDIES

Thesis Chairman: Dr. Charles J. Bridgman

Approved for public release: IAW AFR 190-17.
Lynn E. Wolaver
LYNN E. WOLAVER
Dean for Research and Professional Development
Air Force Institute of Technology (ATC)
Wright-Patterson AFB OH 45433
7 May 84

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
Dr. Charles J. Bridgman	513-255-2012	AFIT/ENP

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

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SECURITY CLASSIFICATION OF THIS PAGE

A method was developed that enables a tactical ground commander to predict gamma radiation dose rates and infinite doses produced by the rain scavenging of low-yield nuclear airburst clouds. A ground activity distribution per unit area at time t, $A(x,y,t)$, is computed using a distribution of activity in the cloud per meter of altitude, $A(z,t)$. To find the maximum activity grounded, it is assumed 100 percent of the cloud activity is instantaneously deposited on the ground by the mechanism of rain scavenging. This maximum $A(x,y,t)$ is then converted to a maximum dose rate, $\dot{D}(x,y,t)$, from which maximum infinite doses are computed. Maximum dose rate and infinite dose curves vs cloud washout time (after cloud stabilization) are presented for 10 weapon yields ranging from 1.0 kiloton to 0.1 kiloton. It is shown that the radiation hazard levels are insignificant tactical threats at times greater than 36 hours after cloud stabilization.